Karlsruhe Institute of Technology

Institute for Industrial Production

Annual Report 2023

Chair of Energy Economics

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Karlsruhe Institute of Technology (KIT)
Institute for Industrial Production (IIP)
Chair of Energy Economics
Building 06.33
Hertzstraße 16
D-76187 Karlsruhe
phone +49 721 608 44460/44569
fax +49 721 608 44682
info@iip.kit.edu
www.iip.kit.edu

Preface

This annual report from the Chair of Energy Economics at the Institute for Industrial Production (IIP), Karlsruhe Institute of Technology (KIT) presents an overview of our main activities during 2023. The four research groups "Distributed Energy Systems and Networks", "Energy Markets and Energy Systems Analysis", "Energy and Behavior", and "Transport and Energy" have been working on numerous projects on a regional, national and international level to provide decision support in the field of energy economics. We are currently around 20 research and four administrative staff, roughly divided equally between these four groups.

During 2023, we worked on around 15 ongoing national and international research projects and started six new projects. We published around 14 peer-reviewed journal articles, 15 conference papers and seven PhDs were completed.

My staff and I hope that we can arouse your interest in our research activities with the brief report. We look forward to receiving any comments and suggestions you may have.

Prof. Dr. Wolf Fichtner, Chair of Energy Economics

Distributed Energy Systems and Networks Group

Head of research group: Dr. rer. pol. Armin Ardone

Members of the research group (fltr): Rafael Finck, Max Kleinebrahm, Leandra Scharnhorst, Thorben Sandmeier, Armin Ardone, Alexander Plarre, Julia Schuler, Viktor Slednev.

The promotion of renewable energy sources (RES) and combined heat and power (CHP) generation leads to an increasing decentralisation of energy systems and brings about new challenges. Especially in Germany, the realisation of the ambitious targets concerning the expansion of RES necessitates an extensive structural rearrangement of the system. For instance, large amounts of electricity need to be transported from the wind farms in the north to the large load centres in southern and western Germany. As a consequence, the grid load in the system will rise to an extent that is hardly manageable with existing power grid capacities. Furthermore, decentralised power generation installations (e.g., solar PV) need to be integrated into the lower voltage power grids without violating grid-safety constraints. In this context, different market design options for distributed energy systems, including appropriate demand response mechanisms, are currently being intensively discussed. However, the consequences of these structural changes for the system's stability and resilience are not yet well understood.

In addition, the number of players in the market recently increased in consequence of the decentralisation and this number is expected to further increase. Since the different players typically pursue different objectives and have different preference perceptions, multiple and usually conflicting targets need to be considered. As a result, decision and evaluation processes need to be designed in a participatory way. Moreover, a purely economic optimisation is no longer sufficient to support decision making in energy systems since the importance of ecological, technical and socio-psychological criteria steadily increases.

Energy Markets and Energy System Analysis Group

Head of research group: Dr. rer. pol. Emil Kraft

Members of the research group (fltr): Thorsten Weiskopf, Florian Zimmermann, Anthony Britto, Stephanie Stumpf, Julius Beranek, Emil Kraft. Missing in picture: Johannes Schuhmacher, Eric Jahnke.

The design of sustainable energy systems under consideration of environmental, economic, social and security aspects is not only an important, but also a complex task. On the one hand, the task requires strong political governance with a broad view for possible future developments. On the other hand, the task is dependent on decisions and the behaviour of different actors in the sectors of energy generation, trade, supply and usage. The turbulent year 2022 has once more shown the significance of energy markets and the supply with energy on all facets of modern societies and particularly the economies. The goal of the research group Energy Markets and Energy System Analysis (EMESA) is the

formulation and application of various types of quantitative models to analyse the implications of political and economic framework conditions as well as technological trends onto the future development of energy systems.

The main research topics include

- security of supply,
- electricity market design,
- investments in flexibility options and decarbonisation technologies,
- economics of energy storage on different time scales,
- system integration of renewable energy, and
- decisions under uncertainty in energy markets.

For the analyses on these topics, both, the overall economic perspective and the market participants' individual perspectives are taken into account. The targeted audience for the studies of the research group EMESA are decision-makers from politics, business and industry.

Energy and Behavior Group

Head of research group: Dr. Daniel Sloot

Members of the research group (fltr): Dr. Daniel Sloot, Stephanie Stumpf, Nora Baumgartner

The Energy and Behavior Group investigates the acceptance and adoption of innovations in the context of the energy transition, as well as other topics related to sustainability transformations, from a social and behavioral perspective. Using empirical social research theories and methods, the group primarily researches the individual drivers and barriers affecting acceptance and adoption. Among other things, their research includes experimental methods (randomized controlled trials), correlational panel studies, and field studies. Current topics include the diffusion of electric heat pumps, acceptance of bidirectional charging of electric vehicles, and the acceptance of negative emissions technologies.

Transport and Energy Group

Head of research group: Manuel Ruppert

Members of the research group (fltr): Uwe Langenmayr, Alexandra Märtz, Manuel, Nora Baumgartner, Christian Perau, Thomas Dengiz, Tim Signer.

The ongoing decarbonisation of the energy sector and its increasingly rapid transformation pose a variety of complex questions for research. While questions with a strong focus on the electricity sector have traditionally been investigated in the field of energy system analysis, questions concerning the optimal system design across the individual sectors (sector coupling) are currently particularly relevant. In the context of these questions, the working group Transport and Energy at the Chair of Energy Economics performs research on coordinated emission reduction strategies in the sectors electricity, gas, heat and transport. A special focus is on the mobility transition through increasing electrification of the transport sector. Currently, one promising alternative in this regard is the electrification of passenger road transport by electric vehicles (EV). They come along with a significant increase in energy efficiency and a shift in fuels: from oil dominated to a high diversification potential via the energy carrier electricity. Furthermore, they accelerate the interactions of the transport and the electricity system, which is a central area of research within the group. Another special field of interest in this context is the coupling of the electricity and the gas sector using power-to-X technologies and the subsequent link to transportation when producing renewable fuels (power-to-liquid).

The group currently follows three central questions of research: First, the market development of EV is investigated concerning market penetration and impact of smart charging methods on the local and national power system. Second, the feasibility of energy storage and power-to-X technologies in the future energy system is being analysed on both local (distribution grid) and central (transmission grid) level, also considering interdependencies and interaction with electricity and gas infrastructure. Third, mobility patterns, user behaviour and user acceptance analyses of (technological) innovations in the transportation sector are performed. For answering these research questions, we apply highly interdisciplinary approaches from business economics, economics, sociology, electrical engineering, logistics, and other environment-related disciplines and with strong cooperation with electrical engineers and computer scientists. Our main methods are based on energy system modelling, such as optimisation tools, agent-based simulation, econometrics as well as other socio-economic or mathematical models. We have a comprehensive exchange with international partners from academia and industry. Funding of the research projects in the group is provided by national and federal German ministries, the European Commission, and industry.

Outlook: The new Group Structure

The groups were reorganized at the end of the year. The new groups and their members are briefly described below.

Sustainable Infrastructures for Renewable Energy Systems Group

Head of research group: Rafael Finck



Members of the research group (fltr): Rafael Finck, Christian Perau and Thorben Sandmeier

The research group aims at developing tools, methods and datasets for scenario-based techno-economic analyses for electricity, gas and hydrogen transport networks in the context of European decarbonisation goals. Research covers for instance the integrated planning and operation of transport networks for electricity, gas and hydrogen, the techno-economic analysis of new components for electricity grids, the interdependencies between market design and grids, the effects of sector coupling technologies on infrastructures and empirical behaviour studies in the living lab Energy Smart Home Lab.

Energy and Behavior Group

Head of research group: Dr. Daniel Sloot

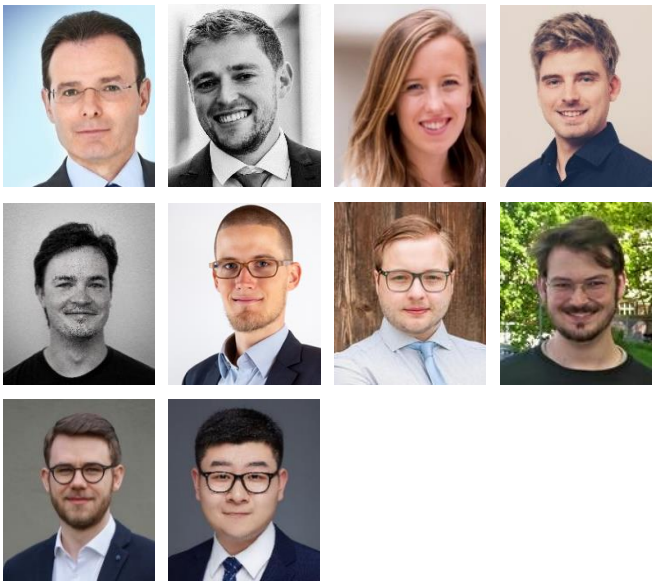


Members of the research group (fltr): Dr. Daniel Sloot, Stephanie Stumpf, Nora Baumgartner

The Energy and Behavior Group investigates the acceptance and adoption of innovations in the context of the energy transition, as well as other topics related to sustainability transformations, from a social and behavioral perspective. Using empirical social research theories and methods, the group primarily researches the individual drivers and barriers affecting acceptance and adoption. Among other things, their research includes experimental methods (randomized controlled trials), correlational panel studies, and field studies. Current topics include the diffusion of electric heat pumps, acceptance of bidirectional charging of electric vehicles, and the acceptance of negative emissions technologies.

Sustainable Energy Markets and Future Energy Commodities Group

Head of research group: Dr. rer. pol. Armin Ardone and Victor Slednev



Members of the research group (fltr): Armin Ardone, Victor Slednev, Julia Schuler, Eric Jahnke, Uwe Langenmayr, Thorsten Weiskopf, Julius Beranek, Alexander Plarre, Johannes Schuhmacher, Wenxuan Hu

This group focuses on two main research areas. One being the analysis of market design alternatives as well as market price forecast. Main tools are agent-based models of electricity markets with a particular focus on capacity mechanisms in systems with high shares of renewables including impacts from flexibility (e.g., storages) and cross-border effects. The other one focusses on model-based energy systems analysis from regional to global scale with high temporal and spatial resolution including optimized adaptation of infrastructures. The conversion, transportation and storage of future energy commodities include hydrogen and derivates as well as reactive metals

Energy Demand and Mobility Group

Head of research group: Max Kleinebrahm

Members of the research group (fltr): Max Kleinebrahm, Leandra Scharnhorst, Thomas Dengiz, Tim Signer, Anthony Britto

The research group 'Energy Demand and Mobility' conducts research on coordinated emission reduction strategies across the energy, mobility, household, and industry sectors. To better understand the future uptake of low-carbon technologies and efficiency measures within and interdependencies between sectors, we apply highly interdisciplinary approaches from economics, engineering, computer science, and sociology. Our main methods are based on energy system modeling, such as optimization tools, agent-based simulation, machine learning, econometrics as well as socio-economic empirical approaches. We have a comprehensive exchange with international partners from academia and industry. National and federal German ministries, the European Commission, and industry provide funding for the research projects in the group.

Research Projects

AsimutE: Intelligent self-consumption and storage for better use of energy

Thomas Dengiz, Daniel Sloot, Stephanie Stumpf, Max Kleinebrahm, Manuel Ruppert

Partner: Université de Haute-Alsace, Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, Hochschule Offenburg, Hochschule Furtwangen, Centre National de la Recherche Scientifique, Hochschule Kehl, Albert-Ludwigs-Universität Freiburg, Fachhochschule Nordwestschweiz FHNW

Funding: Interreg Oberrhein

Duration: 10/2023 to 01/2027

The ASIMUTE project investigates solutions for optimized and safe energy use and storage by involving end users throughout the project. The aim is to achieve a balance between energy demand and the production capacity of renewable energies, taking into account the available storage options. The project partners will use artificial intelligence methods and conduct surveys among consumers, energy suppliers and stakeholders in the Upper Rhine region. The project is multidisciplinary as it will cover aspects from both a techno-economic and a social science perspective. The legal feasibility in the trinational context as well as the acceptance by end consumers in the different cultural contexts of the three countries will be investigated. This will be based on findings from sociological, legal and technical studies that have emerged from the Interreg projects "*Vehicle*" and "*Advanced Control Algorithms for the Management of Decentralised Energy Systems*".

The DFIU is involved in several parts of the project. Together with the Université de Haute Alsace, the effectiveness of calls to save energy in private households is being investigated, taking into account psychological compensation mechanisms. In addition, the expectations of private households with regard to technologies for self-consumption of energy are being investigated with the help of qualitative and quantitative empirical studies.

The DFIU is also involved in the development of methods for the multi-objective optimization of heating systems in representative residential areas of the respective countries. In addition to energy costs, greenhouse gas emissions, thermal comfort and electrical load peaks are optimized in simulations. As the objectives in a residential area are often contradictory, multi-objective optimization methods in combination with machine learning methods are particularly suitable.

BDL – Bidirectional Charging Management

Tim Signer, Nora Baumgartner, Manuel Ruppert

Partners: BMW, TenneT, Bayernwerk, KOSTAL, Forschungsstelle für Energiewirtschaft, Universität Passau, KEO

Funding: Federal Ministry for Economic Affairs and Climate Action (BMWK)

Duration: 2019 to 2022

Under the consortium leadership of BMW, the BDL project aims at developing electric vehicles and the

supportive hard- and software for bidirectional charging ("Vehicle-to-Grid", or V2G) and testing those for different use cases in a field test. 20 households are involved in testing the use cases intraday trading and vehicle-to-home. The pilot phase started in August 2021 and lasts until the end of 2022. Besides private households, eight companies participate in the testing of a total of eight use cases. For example, the objective is to raise the pooled potential of company EVs to reduce the peak load of the facility. Most use cases are tested in the field, while some use cases are tested using a simulation model. Further use cases are tested in a laboratory environment. All tests are conducted using a V2G-enabled BMW i3.

Apart from the technical development and implementation of the use cases, three research partners were involved in the accompanying research of this project. In this regard, the KIT had a special focus on the question, how to optimally integrate the flexibility and storage capacity of electric vehicles (EVs) into the energy supply system, both from a system's and from the stakeholders' perspectives. For this reason, KIT investigates the interaction of bidirectional charging management with electricity markets and grids in the BDL project.

The existing electricity market model PowerACE has been extended to include the effects of bidirectional chargeable EVs in the analysis. Different simulations to determine electricity market effects of V2G have been conducted. Some of the findings of the pilot phase, where 50 EVs have been tested in different use cases, have been included in the PowerACE simulations.

In order to identify the opportunities and risks for BDL from both an energy system and user perspective, KIT is also involved in user acceptance research and thus supports holistic accompanying research. Specifically, in 2022 several surveys with pilot customers were conducted by the University of Passau and the KIT to gain more insights into the feasibility and acceptance of the bidirectional charging technology.

The final project year was again affected by the COVID-19 pandemic. The project meeting in April 2022 thus took place in a digital format. However, the second project meeting in September 2022 took place in Munich. Here obtained results of the pilot phase were presented and discussed. In view of the approaching end of the project, ways of communicating the results were discussed. Finally, the last project meeting took place in November 2022. Here, the most relevant findings were presented to the partners. All project partners and pilot customers participated at the final event.

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

BDL –Next

Tim Signer, Max Kleinebrahm

Partners: KIT-IIP, BMW, Bayernwerk Netz, TenneT, E.ON, KEO, Compleo, University of Passau and EBZ

Funding: Federal Ministry for Economic Affairs and Climate Action

Duration: 11/2023 to 11/2026

BDL-next aspires to bring bidirectional charging to mass market readiness, overcoming technical, legal, and procedural hurdles. The initiative builds on the BDL project, which highlighted the multifaceted capabilities of electric vehicles for energy markets, grid support,

system services, and user benefits. Essential to this is the smart management of power as seen in self-consumption optimization for solar setups and grid frequency regulation. Currently, technological, legal-regulatory, and procedural gaps still prevent the seamless transition to mass real-world operation of bidirectional charging strategies.

This is precisely where BDL Next begins: The project aims at simplifying and enhancing the technology of bidirectional charging to fit seamlessly into the current energy market and service systems. Work is also being done on the grid-oriented and market-oriented operation of bidirectional vehicles, so that they may become an integral part of our robust and intelligent power grid. A multi-stage field trial will use real-world experiences to identify weaknesses in the concept and technical development, further increase the economic and ecological benefits of bidirectional charging, and simplify the integration of the technology from a customer perspective.

The main tasks of our chair include:

- Analysis of Vehicle-2-Grid cross-border effects.
- Analysis of Vehicle-2-Grid related wholesale market price effects.
- Development of MobiFlex model to estimate V2G flexibility based on new mobility data

The following tasks were carried out in 2023:

- Project start
- Use-case definition with workshop

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

BETS

Thorsten Weiskopf, Armin Ardone

Partners: KIT-IIP, IZES, DTU

Funding: Federal Ministry for Economic Affairs and Climate Action (BMWK)

Duration: 11/2023 to 10/2026

The short-term value of electrical energy is largely determined by trade in the market areas. The hourly day-ahead market in particular serves as a reference market for the futures products and end customer prices. The electricity producers offer a generation price per megawatt hour (MWh) on the electricity exchange, which reflects the variable costs of power plant operation. This marginal cost indicates the cost of the next unit of electricity to be produced. However, it must be questioned whether bidding based on marginal costs will continue to exist in a much more heterogeneous power plant portfolio that is traded on the stock exchange in the future. The continued increase in electricity generation from renewable energy systems will significantly change the characteristics of the merit order. At the same time, market consolidation into an oligopolistic structure is possible due to cost advantages, as is currently being observed with offshore wind energy. This market organization continues to allow strategic behavior on the electricity market, especially in situations of shortage. From the perspective of all market participants, strategic imperatives may appear necessary in the new market environment. A paradigm shifts away from a marginal cost-based merit order towards an opportunity cost-based or marginal costs plus markup-based merit order seems to be expected. Essentially, these considerations lead to the hypothesis that such bidding strategies can occur more frequently:

a) the greater the differences in technology-induced marginal costs

b) the more different the generation park is in market areas

c) the less flexibility is available within a market area

d) the greater the available transmission capacities between market areas.

As part of the project, the bid data available at EPEX SPOT in the price curves of individual market areas will now be analysed for strategic patterns. The price curves represent the aggregated behavior of all market participants. In a second step, the strategies found will be tested in the future and their influence on the electricity price and investments in flexible generation technologies in Germany will be examined, taking into account the very different national electricity generation systems in Europe in the future. The goals of the system analysis project are therefore the following:

1. Bidding strategies have been identified from the existing bidding curves that lead to electricity market price increases compared to marginal cost-based bids.

2. The relevant bidding strategies are depicted in European electricity market models via a learning agent.

3. The influence of the bidding strategies on electricity prices and investments in a future electricity system with high shares of renewable energies and storage is determined.

CARE-o-SENE - Catalyst Research for Sustainable Kerosene

Paul Heinzmann, Uwe Langenmayr, Andreas Rudi, Manuel Ruppert

Partners: Sasol Ltd; Sasol Germany GmbH; Helmholtz-Zentrum Berlin für Materialien und Energie (HZB); Karlsruher Institut für Technologie (KIT): IKFT, IIP; University of Cape Town, Department of Chemical Engineering (UCT); Fraunhofer Institute for Ceramic Technologies and Systems (IKTS); Ineratec GmbH

Funding: Federal Ministry of Education and Research

Duration: 10/2022 – 10/2025

The Power-to-Liquids (PtL) strategy is the future key to a sustainable decarbonization of hard to abate sectors, such as the aviation sector. The PtL approach can produce sustainable aviation fuels (SAF) by utilising Fischer-Tropsch (FT) processes to convert green H2 and sustainable carbon dioxide. A decisive success factor for viable long-term SAF PtL projects will be a competitive FT catalyst with high conversion efficiencies and yields to the desired SAF product, for which demand is expected to grow rapidly in future. The goal of CARE-o-SENE is the accelerated and knowledge-based development of Fischer-Tropsch catalysts for the highly efficient and sustainable production of green SAFs in relevant volumes for the transformation of the aviation sector. The IIP will contribute to this project with the techno-economic analysis of the developed processes and technologies.

Supported by:
Federal Ministry of Education and Research
on the basis of a decision by the German Bundestag

SPP 2403: Carnot Batteries: Inverse Design from Markets to Molecules

Armin Ardone

Partners: Karlsruher Institut für Technologie; Universität Duisburg-Essen; Universität Bayreuth; Technische Universität Dortmund; Technische Universität Ilmenau; Technische Universität Berlin;

Ruhr-Universität Bochum; Gottfried Wilhelm Leibniz Universität Hannover; E.ON Energy Research Center; Rheinisch-Westfälische Technische Hochschule Aachen; Technische Universität Braunschweig; Technische Universität Darmstadt; Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR); Technische Universität Dresden; Technische Universität Berlin

Funding: German Research Foundation (DFG)

Duration: 2023 –2026

This project aims at investigating promising CB (Carnot Batteries) configurations, the potential role of CBs in future energy systems, as well as economic incentives and barriers for a successful market entry. As technical CB development is still in progress, energy economics can provide an orientation towards promising directions. This motivates a novel inverse approach to investigate the role of CBs in future energy markets. Such an inverse approach is new to energy market modellers and brings challenges with it. Hence, we aim at depicting CBs in an agent-based market model depicting Germany and its neighbours to identify economically attractive technical configurations and their use in the system, to derive potential profit-risk structures for CBs as an investment option, and to assess inevitable techno-economic trade-offs from a market perspective.

The major challenge consists of the adequate depiction of the market functioning through individual economic decisions. A working programme consisting of six working packages addresses this challenge and thereby deploys an agent-based electricity market simulation. Whereas optimisation approaches usually identify desirable investment and dispatch decisions in a normative manner taking a central planner perspective, the agent-based approach is not dependent on generally assuming perfect foresight and perfect coordination. It is able to depict the market structure and market participants' individual decisions.

The key objectives of the project are threefold: On the one hand, the goal is to integrate the inverse engineering character into agent-based energy system modelling by modelling techno-economic characteristics as decision variables of the agents. This requires extensive methodological developments, both in the short- and in the long-term decision-making of agents. On the other hand, the technical representation of the CB's characteristics requires model enhancements. Particularly the differentiation, interplay and potential profit cannibalisation of competing flexibility options led to challenges, as many degrees of freedom complicate convergence, if the techno-economic properties are very similar or agents face immanent uncertainties in their strategic decisions. The third objective is to develop a framework for assessing profit-risk structures of promising technical configurations, based on mean-reverting and path-dependent energy system uncertainties. Path-dependent uncertainties such as the development of new technologies or renewable capacity expansion require endogenous treatment in the simulation model. We propose extension of the existing agent-based model to derive, among others, dispatch curves for different CB configurations under varying market circumstances, as well as profit-risk structures for CBs from an individual market participant's perspective.

Clean Circles

Julia Schuler, Viktor Slednev, Armin Ardone

Partners: TU Darmstadt, JGU Mainz, DLR, Max-Planck-Institut für Eisenforschung

Funding: Strategy Fund of the KIT Presidium

Duration: 01.06.2022-31.12.2024

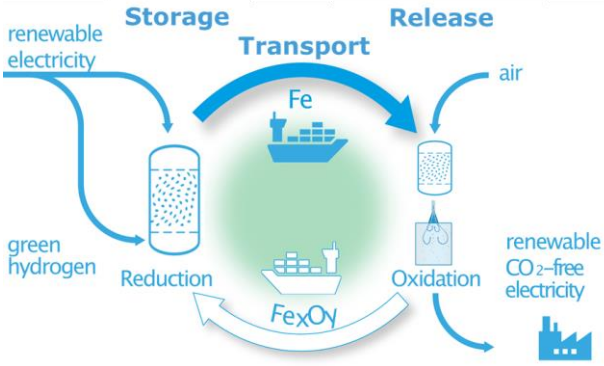
The interdisciplinary research project Clean Circles evaluates a future carbon-free circular energy economy based on iron and its oxides as a renewable energy carrier.

The consortium is currently applying for funding under the DFG EXTRA "Exzellenzcluster" line, which will begin in January 2026.

The technical concept is illustrated below:

Renewable energy (e.g., hydrogen) is used to chemically reduce iron oxide to store energy in iron powder. $Fe_2O_3 + 3\ H_2 \longrightarrow 2\ Fe + 3\ H_2O$

After being shipped to the demand destination, the iron powder is combusted to release the stored energy for example for electricity production, ideally using existing infrastructure such as retrofitted coal fired power plants. $2\ Fe + 3/2\ O_2 \longrightarrow Fe_2O_3$



The main properties that make iron particularly attractive as a storage medium are:

- Availability and price: fourth most abundant element in the earth crust
- non-toxicity
- high volumetric energy density (16,5 kWh/l compared to 2,4 kWh/l for liquid hydrogen)
- oxidation flame temperatures and residence times similar to hydrocarbons

Those properties as well as preliminary studies at TU Darmstadt, TU Eindhoven and McGill University Montreal give reason to be optimistic that iron can enable large-scale storage and transport of renewable energy as well as the reuse and retrofit of existing infrastructure, namely power plants and proven transport routes for bulk material such as ships, railway and ports.

Within the interdisciplinary framework of Clean Circles with over 20 subprojects in engineering, natural, humanities and social sciences, the Chair of Energy Economics will bring in its competence in energy system analysis. Model-based investigations on the potential of iron as fuel in power and heat sector, industry, GHD and transport will be carried out, as well as a comparison of iron to alternatives (e.g., liquid H_2, NH_3, synfuels) and the evaluation of regions worldwide regarding their suitability for the reduction process. Answers will be provided regarding the role of iron within Europe's energy transition, with focus on the contribution to reduce costs by building on existing infrastructures. The application of spatially and temporally highly resolved energy system models existent at KIT, such as PERSEUS-gECT (global Energy Conversion and Transmission), allows to reach a level of detail which will provide valuable political decision support.

Clean Circles

CO2Inno - Real laboratory CO2-neutral innovation region Upper Rhine

Nora Baumgartner, Daniel Sloot

Partners: University of Freiburg, University Haute-Alsace, TRION-climate e.V., University of Applied Science Karlsruhe, City of Offenburg, Collectivité européenne d'Alsace, University of Strasbourg, University of Applied Science Kehl, Klimapartner Oberrhein e.V., Badenova AG & Co. KG

Funding: European Regional Development Fund (ERDF) under the INTERREG VI Upper Rhine Programme

Duration: 10/2022 to 09/2025

CO2InnO

The project "CO2Inno" is coordinated by the University of Freiburg. Ten other financed partners from Germany and France are represented in the project consortium. The European Union is supporting the project with a total of 2.556.522 million Euros from the European Regional Development Fund (ERDF). The objectives of the project are the following:

1. To promote the technical development and societal anchoring of selected technologies and approaches in the field of sustainable energy and mobility systems (cogeneration unit, e-mobility, smart grid, smart meter and cyber security) in cooperation with the operators of two selected public institutions in the region (DE/FR).

2. A comparative analysis (Germany/France) of the legal-administrative feasibility and social acceptance of the tested technologies and approaches and derivation of recommendations.

3. An assessment of the overall environmental impact of reusing a former nuclear site for the development/implementation of low-carbon energy solutions.

4. The participatory involvement of key regional stakeholders from Germany and France in the design, implementation and dissemination of the project.

5. To raise awareness among politicians and the general public by presenting, discussing and further developing the climate-friendly solution approaches for sustainable energy and mobility within public events and involving economic actors in finding solutions.

The key findings will be incorporated into a guidebook that provides policy recommendations for the acceptance of cross-border use of decarbonizing technologies across multiple dimensions: technological, legal-administrative, and societal.

The KIT-IIP/DFIU is responsible for conducting research with a focus on technology acceptance. In 2023, the research team started off with a systematic literature review on factors affecting the acceptance of hydrogen-based technologies. Furthermore, the team created a database with best practice examples of municipalities that plan on using a hydrogen-fueled CHP unit. The best practices will be examined in more detail in 2024 by conducting interviews with experts and by evaluating possibilities to transfer the lessons learned to the municipal partners of this project.

Moreover, DFIU started to conduct research on the acceptance and risk perception of smart meter technology. It is especially interesting to do a country comparison, as France has already completed the smart meter rollout, while Germany lags behind. This is why we conducted a survey on the risk perception of smart meters, perceived barriers, and opportunities for the energy transition in both countries. The research is embedded in a university teaching format, led by KIT-IIP/DFIU.

Finally, the first colloquium was carried out in December 2023, where the project partners presented first results to the public. The KIT team participated by disseminating research insights in through a panel discussion.

En4U - Entwicklungspfade eines dezentralen Energiesystems im Zusammenspiel der Entscheidungen privater und kommerzieller Energieakteure unter Unsicherheit

Daniel Fett, Daniel Sloot, Stephanie Stumpf

Partner: Deutsches Zentrum für Luft- und Raumfahrt (DLR), KIT - Institut für Operations Research (IOR)

Funding: Federal Ministry for Economic Affairs and Energy

Duration: 04/2021 to 07/2024

The En4U project investigates uncertainties in the energy market and their impact on household energy decisions using three technologies with different market diffusion (PV battery storage systems, electric vehicles, and heat pumps).

The aim of the project is to analyse and understand the influences of uncertainties on the operation and investment decisions of households regarding these

three technologies. In this course, the project partners also evaluate the effects on the operation and investment of portfolios of modern conventional and renewable power plants in combination with storage capacities. First, the uncertainties of the energy actors are explored and quantified. This includes not only economic, meteorological or political uncertainties, but also societal aspects, which are often neglected in energy market research. Therefore, demographic and psychological determinants of technology adoption were empirically investigated through a representative study. Building on this, the future adoption of the aforementioned technologies is analysed using bass diffusion modelling and an allocation of typical German sample households based on a clustering of the survey findings.

By developing and applying suitable methods of stochastic optimization, uncertainties for operators of conventional as well as renewable power plant portfolios are modelled and their decisions optimized.

The focus of this research is on the diffusion of the technologies considered and the expected transformation pathways for the development of conventional and renewable power plant capacities.

Supported by:

on the basis of a decision
by the German Bundestag

Energy Status Data – Informatics Methods for its Collection, Analysis and Exploitation (DFG Graduate School 2153)

Alexander Plarre, Eric Jahnke

Partners: Karlsruhe Institute of Technology: IPD, IIP, ITI, ITEP, IAI, KASTEL, ZAR, IPE, IISM

Funding: German Research Foundation (DFG)

Duration: 2016 to 2025

The design of future energy systems which can cope with fluctuating supply and flexible demand is an important societal concern. An essential aspect is the consumption of energy, particularly of complex systems such as factories or IT infrastructures. Important points are the flexibilization of energy consumption, robustness of energy provisioning, or the efficient design of new energy systems serving these purposes. To accomplish this, a core prerequisite is a structured collection, storage and analysis of energy status data, which is data that describes the provisioning of energy, its storage, transmission and consumption.

Within the scope of this graduate college, we focus on investment in energy technology using tools from decision theory and operations research. The goal of this research is to first understand the investment behavior of agents in different sectors of the energy economy, and consequently, to map out patterns of investment (i.e., technology diffusion) that emerge at a macro level.

ENERGY
STATUS
DATA
COLLECT • ANALYSE • UTILISE

Energy System Design (ESD)

Armin Ardone, Max Kleinebrahm, Thorben Sandmeier, Leandra Scharnhorst

Partners: Forschungszentrum Jülich (FZJ), German Aerospace Centre (DLR), HELMHOLTZ Center Berlin (HZB), Max-Planck-Institute for Plasma Physics (IPP) and Karlsruhe Institute of Technology (KIT)

Funding: Helmholtz Research Program (PoF IV)

Duration: 2021 to 2027

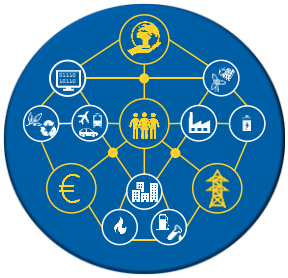
The primary objective of the Program is to provide the necessary expertise to enable the success of the energy transformation on system level. There are two broad, inter-linked strands to the Program: Topic 1 examines different transformation pathways for the energy system embedded in their full technical, economic, environmental, societal and political contexts, while Topic 2 provides methods and technologies for the detailed design and operation of future integrated energy systems. Both Topics cover a time horizon up to the year 2050 with an indicative outlook beyond. The objectives are:

- to establish a set of three to five different but internally-consistent and plausible qualitative and quantitative scenarios for the energy transformation, so that they can provide system knowledge down to the technical requirements. (Topic 1)
- to use these transformation scenarios to develop decision support tools for policymakers and to investigate them in societal real-world laboratories and with other inter- and transdisciplinary tools. (Topic 1)
- to develop detailed methods and technologies on a systems level to plan and operate resilient, decentralized and integrated energy systems. Systems technologies will be demonstrated and validated in smart energy system laboratories under close to real conditions. (Topic 2)
- to identify the technical pre-conditions for the feasibility of the energy system in 2050 in both redemonstrating this feasibility using the real-world implementations of the different technical solutions. (Topic 2)

The IIP is involved in subtopic 2.2 "Design, operation and digitalization of future energy grids" and subtopic 2.3 "Smart areas and research platforms". In 2.2 we participate in the efforts to develop new models for future energy grids. In this context modern optimization algorithms for solving large-scale power grid simulations shall be developed and applied and the role of flexible network elements like FACTS, PST and battery storage systems in a world of rising renewable energy generation shall be evaluated. Additionally, the needed market design options in order to ensure that the technical solutions regarding the new system challenges can be build, financed and operated based on economic sound decisions will be analyzed.

In 2.3 the IIP is using the Energy Smart Home Lab, a residence building which is part of the Energy Lab 2.0. It is equipped with modern technical equipment like a PV-system, a battery storage system and a combined heat and power generator, measuring systems for all the power and heat flows and an energy management system. In our research, we investigate topics such as strategies for rewarding flexible use of energy and energy efficiency improvements, the economic value of security of supply, the interoperability between a smart home energy management system and smart grids or the interactions between self-sufficiency and electromobility. In practice, we conduct long-term residential periods with up to two external persons in a close to real life environment. During these experiments, we provide the inhabitants with information, messages and incentives and observe their reactions via smart meter data, surveys and interviews. Based on the data the user behavior and acceptance are evaluated. For instance, this year we confronted users with temporary, planned power shutdowns in order to investigate and quantify their willingness to pay (to avert a shutdown) and willingness to accept (a shutdown) associated to the security of supply. Furthermore, we will provide the collected quantitative data to our partners.

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES



ENSURE 2 – New Electrical Grid Structures for the Energy Transition

Julius Beranek, Christian Perau, Rafael Finck, Armin Ardone

Partners: ABB Power Grids Germany AG, Bergische Universität Wuppertal, CAU, DUH, DVGW-EBI, EWI, FAU, FGH, FH Westküste, Germanwatch, KIT, Maschinenfabrik Reinhausen, OFFIS, Öko-Institut, RWTH Aachen, SH Netz, Siemens AG, SWKiel Netz GmbH, TenneT, TU Dortmund, TU Ilmenau

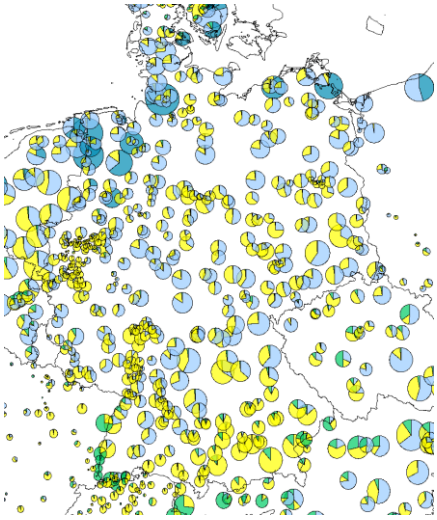
Funding: Federal Ministry of Education and Research

Duration: 02/2020 to 01/2023

The project ENSURE examines and demonstrates technical solutions for the energy networks of the future over a period of ten years and three project phases as part of the funding initiative Kopernikus-Projects for the energy transition. The research work in the second phase will contribute to making the energy system transformation economically successful. The project aims in particular to answer three questions:

- How will the supply tasks change beyond 2030, taking into account future and changing social, economic and ecological conditions?
- What technical challenges will result from the changing supply tasks for energy infrastructures?
- What network structures and technologies should be used to meet these challenges?

The results achieved in ENSURE 2 are the basis for different demonstrations in phase 3. A holistic concept for the supply of energy has been created. This concept is embedded in the socio-economic context and ensures transferability of the results within Germany and Europe. Tests regarding electrical grids have been conducted successfully applying digital twins.



Installed renewable capacities in one of the ENSURE-storylines

At the IIP, we investigated different topics in the subprojects "Socioeconomic analysis" and "Integrated system structures" together with our partners. This involves investigating the effects of different market designs on the investment and bidding decisions of various actors and the interactions with the operations in congestion management of the electrical transmission network. The results showed a clear improvement of self-sufficiency for Germany when introducing a capacity market in the energy system. Due to this a decrease in interregional exchange flows could be observed when investigating the necessary redispatch measures. Furthermore, generation and load time series with regionally and technically high-resolution for different scenarios in the electricity system of the future were simulated at the IIP on a European scope. In addition to the above-mentioned question, these simulations also form the basis for investigations by other project partners at the transmission and distribution network level.

Supported by:

Federal Ministry of Education and Research

on the basis of a decision by the German Bundestag

ENSURE 3 – New Electrical Grid Structures for the Energy Transition

Christian Perau, Julius Beranek, Rafael Finck, Armin Ardone, Emil Kraft, Manuel Ruppert

Partners: AllgäuNetz GmbH & Co. KG, Avacon Netz GmbH, BUW, CAU, DUH, DVGW-EBI, E.ON, eMessage, EWI, FAU, Germanwatch, Hitachi Energy, Hochschule München, KIT, LVN, Maschinen Fabrik Reinhausen GmbH, Öko-Institut, OPAL RT Technologies, PSI Software AG, RWTH, Siemens AG, SWB, swa, SW Kiel, Stadtwerke Meerbusch, TU Dortmund, TU Ilmenau, TenneT TSO GmbH, Westfalen Weser Netz

Funding: Federal Ministry of Education and Research
Duration: 01.08.2023 – 31.07.2026

The project ENSURE examines and demonstrates technical solutions for the energy networks of the future over a period of ten years and three project phases as part of the funding initiative Kopernikus-Projects for the energy transition. In phase 3, ENSURE addresses the following key challenges to the electrical grids as the backbone of the energy transition:

- The geographic focal points of generation and consumption are shifting. The electrical grid must be adapted for longer distances and increasing capacities.
- The electrical grid must support the coupling with other energy sectors (gas, mobility, buildings) and enable synergies ('sector integration').
- The fluctuating power input of renewable sources must be balanced.
- The necessary system services must still be provided and coordinated even after the decommissioning of large power plants.

At the IIP, in ENSURE 3 questions in the subproject "Integrated structure for a future grid with central and decentralized supply elements" in the clusters "Systematic Evaluation of ENSURE solutions" and "Market and Grid Regulation as well as Market Design" are investigated. This involves investigating the potential advantages of integrated infrastructure planning by municipal or regional entities and to develop the necessary regulatory framework for this integration at various grid levels.
Furthermore, an understanding should be developed of how the interdependence of regulation and market design questions ensures the necessary investments to guarantee a secure electricity grid in the future.

Supported by:
Federal Ministry of Education and Research
on the basis of a decision by the German Bundestag

FlexKälte

Thomas Dengiz, Manuel Ruppert

Partners: KIT-IAI (Institute for Automation and Applied Informatics), Forschungszentrum Informatik (FZI), Stadtwerke Karlsruhe GmbH, Seven2one Informationssysteme GmbH

Funding: Federal Ministry for Economic Affairs and Climate Action (BMWK)

Duration: 01/2020 to 03/2023

The project "FlexKälte" (Joint project: *Investigation of existing cooling systems in order to use flexibilities in a real-world application*; sub-project: *Campus instrumentation for optimal cooling system control*) has the aim to develop a methodology to make use of the flexibility of decentralized, cold producing and cold using plants existing in a property. Besides the identification of the flexibility potential, the "FlexKälte" project focuses on the demonstration of the practical feasibility of an efficient and economic operation of cooling in a real-

world application, while at the same time ensuring the identified boundary conditions, such as user comfort.

Within the scope of the project, distributed cooling applications at KIT Campus North will be instrumented, connected, and virtually combined for central control. First, different optimization strategies to be developed are tested with a large number of cooling systems in a simulation and then the practical implementation is realized in an exemplarily. The intended central management should enable the virtual network to serve as cooling capacity/storage in the overall system and thus - beyond operational optimization - to react on changing supply network conditions.

The following picture shows an overview of the different tasks of the whole project.

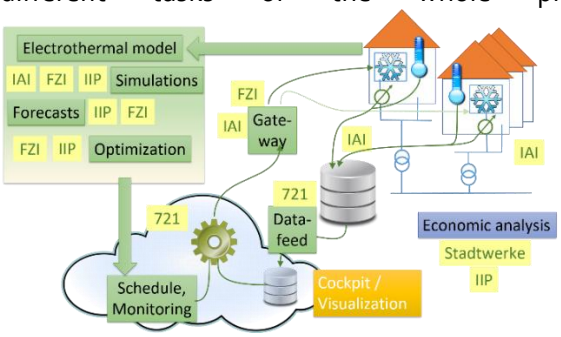


Figure taken from the Institute for Automation and Applied Informatics (IAI), Karlsruhe Institute of Technology

The main tasks of our chair include:

- Design of optimization algorithms for multiple cooling units
- Analysing the available flexibility at KIT Campus North
- Forecasting the cooling demand
- Economic analysis of the load flexibility potential

The following tasks were carried out in 2022:

- Forecasting of the cooling loads and the (inflexible) electricity loads for the relevant buildings
- Analysis of measured electricity load data from the cooling devices
- Design of a model-free optimization algorithm for demand side management of buildings with multiple-zones

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

flexQgrid - Practice-oriented implementation of the quota-based grid light concept for flexibility uses in and from the distribution grid

Daniel Sloot, Nico Lehmann, Armin Ardone

Partners: 9 partners from industry and science: Netze BW GmbH, Entelios AG, PSI Software AG, University of Stuttgart, Karlsruhe Institute of Technology (KIT), BlockInfinity GmbH, Fichtner IT Consulting GmbH, FZI Forschungszentrum Informatik

Associated partners: PREdistribuce, a.s.,

Funding: Federal Ministry for Economic Affairs and Climate Action (BMWK)

Duration: 2019 to 2023

The flexQgrid project aims to make a significant contribution both to the realization of flexibility provision in the distribution grid and to the provision of flexibility for upstream voltage levels.

In flexQgrid, the approaches developed in the grid-control project (www.project-grid-control.de) for a quota-based traffic light concept are further

developed and tested. With an intraday implementation of the quota model and the establishment of secondary trading, further flexibility potential can be provided in the distribution grid. It is essential that asset operators (e.g., private individuals or industrial companies) are willing to provide flexibility. For this reason, appropriate incentives for providing flexibility are being investigated and stakeholders are being involved. In addition, the technical framework conditions that have to be considered before and during the implementation of a quota model are also examined. Finally, the compatibility of the quota model with the legal and regulatory framework is examined and adjustment options are elaborated.

The developed solutions are field-tested. The aim is to use the infrastructure of smart meters like those that are currently being installed in Germany. In addition to battery storage and generation plants, sector-coupling flexibility options (e.g., heat pumps, electric vehicles) and other flexible consumers are to be integrated. In order to ensure a reliable flexibility provision, the dynamic behavior of these facilities is investigated in simulations and laboratory tests. On the basis of the knowledge gained, recommendations for action are derived and a roadmap with the necessary steps for the use of the quota-based traffic light concept is developed.

Within the framework of flexQgrid, the Chair of Energy Economics investigates the incentives necessary for providing flexibility in the low-voltage grid. The first step focused on the development of suitable instruments, e.g., surveys, experiments and expert interviews, which allow investigating the preferences of flexibility providers and thus the quantification of socio-economic constraints. Subsequently, incentives and motivations for flexibility provision among private households were empirically examined through two representative studies that included a discrete choice experiment and a randomized control trial. Additionally, the potential for flexibility was assessed in commercial and industrial sectors by means of expert interviews, focus group studies, and quantitative studies. Repeated surveys were also conducted among participants of the project's field test. The aim was to achieve reliable and valid results. By doing so, conclusions can be drawn on optimal market design options. The project was successfully concluded in 2023.

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Innofuels platform - networking, further development and framework conditions for the ramp-up of electricity-based fuels and advanced biofuels

Andreas Rudi, Paul Heinzmann, Uwe Langenmayr, Alexander Schneider, Manuel Ruppert

Partners: Karlsruhe Institut für Technologie – IIP, IFKM, IKFT, Mineralölraffinerie Oberrhein GmbH & Co. KG, Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg, Infraserv GmbH & Co. Höchst KG and others

Funding: Ministry of Transport Baden-Württemberg

Duration: 10/2022 to 04/2026

The "Innofuels Platform" is intended to serve as a platform for the exchange of expertise, discussion and networking in order to promote the ramp-up of electricity-based fuels and advanced biofuels. Various fuels and fuel paths and their applicability to different transport modalities will be analysed. In addition, value and logistics chains will be analysed, sustainability calculated and possible market and regulatory issues addressed. The IIP is working across all chairs on the techno-economic analysis with a focus on production.

reFuels-Demo: Research-supported measures for the transformation of plants for climate-neutral fuels (reFuels) to an industrial scale

Andreas Rudi, Paul Heinzmann, Uwe Langenmayr, Manuel Ruppert

Partners: Karlsruhe Institut für Technologie – IIP, IFKM, IKFT, ITAS, DLR

Funding: Ministry of Transport Baden-Württemberg

Duration: 05/2023 to 12/2024

The "reFuels - Rethinking Fuels" project researched the production and use of renewable fuels for various modes of transport. The aim is to power existing combustion engines in aircraft, heavy goods vehicles, commercial vehicles and rail vehicles as well as in vehicle fleets. In order to bring the technologies to an appropriate level of maturity, scaling and development towards industrial implementation is required. The next step is therefore the construction of a demonstration plant that produces around 50,000 tonnes/year of these fuels and serves as a platform for technology developers. Scalability and cost efficiency are crucial and require flexible plant configurations. The project aims to integrate this concept into existing refinery environments, taking into account material flows, costs and environmental impact. To be successful, risks in synthesis, product quality, costs and environmental impact must be minimised. The project addresses these aspects in different work packages that form a coherent approach. The plant concept developed forms the basis on which project planners and companies can build. With the successful realisation of the project, Baden-Württemberg is establishing itself as a pioneer for comprehensive mobility solutions to achieve CO_2 and climate targets.

Project website:
www.refuels.com

RESUR - Design of Robust Energy Systems and Resource Procurement (Helmholtz Platform)

Max Kleinebrahm, Anthony Britto, Johannes Schuhmacher, Eric Jahnke, Emil Kraft, Armin Ardone

Partners: Forschungszentrum Jülich (FZJ), Deutsches Zentrum für Luft- und Raumfahrt (DLR), TransnetBW GmbH, Siemens AG, EnBW - Energie Baden-Württemberg AG, VDA - Verband der Automobilindustrie e.V., DVGW e.V., gwi - Gas- und Wärme-Institut Essen e.V., Uniper Global Commodities SE, Westenergie AG, Stadtwerke Karlsruhe Netzservice GmbH, Brainery Park Jülich GmbH, Thyssengas GmbH, E.ON SE, Amprion GmbH, BASF SE

Funding: Helmholtz Gemeinschaft

Duration: 2022 to 2025

The transformation of our energy system and the achievement of climate neutrality in 2045 are the central social challenges of our time, and are our responsibility. The increasing pace of integration of renewables into the energy system, as well as recent disruptive events such as the war in Ukraine and its impact on the energy system and the economy, have demonstrated the need for a rapid proactive analysis of the fundamental aspects of the energy system and resource procurement for decision-makers in Germany in politics, business, science and society on the basis of highly-detailed, model-supported, and sector-coupled basis. The goal is to support strategic decision-making for supply, and to accelerate the implementation of the energy turnaround in Germany in the European context, as well as including global central imports. Geostrategic aspects, criticality and risk diversification are given special consideration.

Within the scope of this project, the IIP contributes to the modules "Energy and resource markets, energy market design, and economic evaluation" and "Disruptive scenarios and robustness of the energy system." In the first module, the IIP will develop extended energy market models, which can be used to investigate the robustness of energy systems with regard to the effects of disruptive events. In the second module, using PERSEUS, the geographic focus of diversified multimodal imports of renewables into Europe will be extended to global coverage. The influences of disruptive scenarios on the energy system as well as the security of supply of materials and energy carriers relevant for the energy system will be investigated with the help of an impact analysis, and spatially and temporally quantified. This year, a sprint took place in which the impact of a heatwave in 2025 in Central Europe was simulated and the impact on electricity prices on the electricity exchanges and security of supply was analysed.

SEDOS – The Importance of Sector Integration within the Energy Transition in Germany - Modeling with a National Open-Source Reference Energy System

Wenxuan Hu, Viktor Slednev, Leandra Scharnhorst, Armin Ardone

Partners: Institut für Energiewirtschaft und Rationelle Energieanwendung (IER) Stuttgart, Reiner Lemoine Institut (RLI) Berlin, Technische Universität München (TUM), Deutsches Zentrum für Luft- und Raumfahrt (DLR-VE) Stuttgart, Forschungszentrum Jülich (FZJ-IEK-3), Karlsruher Institut für Technologie (KIT)

Funding: Federal Ministry for Economic Affairs and Climate Action (BMWK)

Duration: 2022 to 2024

The terms sector integration or sector coupling have become indispensable in discussions of energy and climate policy. The goal of the research project SEDOS, is to improve the representation of sector integration in energy system models and to establish greater comparability of the models by means of open data. In addition to the orientation towards Open Science, the project thus has the goals of jointly developing a reference data set including documentation for the consideration of sector integration in energy system models for Germany and a coordinated model or system structure for three OS models (oemof, TIMES, FINE) with a focus on the energy system of Germany, which equally takes into account the criteria of transparency and traceability, detailing and simplification as well as balance between the subsectors and solvability of the models. This should substantially improve the robustness, transparency and quality of quantitative analyses. By developing a reference data set for energy system modeling for Germany, a high acceptance in the model scene can be assumed. The development of an OS model structure (reference energy system, RES) is also expected to provide easier access to energy system modelling for modelers and users.

In order to achieve the formulated objective, the work is structured along the four major sub-areas of energy system analysis: (i) data management, (ii) model or system structure (in the form of the so-called reference energy system (RES)), (iii) mathematics and associated solution algorithms in the model frameworks oemof, TIMES and FINE, and (iv) user interface. The focus of the work at KIT is on the parameterization of power-side technologies and structures on the supply side, the model-adequate representation of renewables and the electricity demand oft the tertiary, residential and other sectors (as long they are not specified in other subprojects).

In the current project state, the definition of the reference energy system for the power sector and the parametrization of the electricity supply side is finalized.

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

SynergieQuartier Walldorf - Intelligent networking of actors and digitalized technical systems for a cost-efficient and resilient energy system transformation

Alexandra Märtz, Thomas Dengiz, Manuel Ruppert

Partners: beegy, FZI Forschungszentrum für Informatik, MVV Energie AG, Stadtwerke Walldorf

Funding: Federal Ministry for Economic Affairs and Climate Action (BMWK)

Duration: 07/2020 – 07/2023

The project consortium consists of two research institutes and other partners from industry and is funded by the Federal Ministry for Economic Affairs and Energy within the framework of the 7th Energy Research Program of the Federal Government.

The energy transition in Germany has reached a point at which the simple expansion of renewable energies is not sufficient. The system integration of photovoltaic, charging stations for electric vehicles, battery storage and other decentralized loads as well as generators is becoming increasingly important. The digitization of power grids can play the central role in this. For this, it is crucial to simultaneously address the available technologies, the players in the distribution grid and the further analysis of regulation.

To this end, a field test with 28 selected prosumer households has been conducted since the beginning of 2022. In the field test in Walldorf, we are piloting how decentralized power supply from renewable energies and consumers such as electric cars and heat pumps can be optimally coordinated.

The energy systems of the pilot households were initially equipped with smart metering and control infrastructure: a newly developed control box that intelligently networks energy components on site, an intelligent electricity metering system including a smart meter gateway for secure communication of metering data, a web portal that displays all energy flows in the house, and a charging app for charging one's own electric vehicle at particularly low cost. This allows generation and consumption to be optimally matched. In the pilot households, flexible electricity consumers are matched with the availability of their own electricity and the situation in the power grid. This improves the economic efficiency of the decentralized energy systems - both for the individual participants and for the community.

The KIT-IIP is particularly aims to support a system-serving and sustainable integration of electric vehicles into the energy system. In order to estimate the impact of electric vehicle charging on the electricity grid, the individual mobility and charging behavior of the pilot households is being studied in detail. Here, the focus is particularly on the simultaneity as well as the flexibility potential of the charging processes.

In order to also take the regional aspect into account, within the scope of the project, a model is also being developed to identify spatial areas in which an above-average penetration of electric vehciles can be expected in the future. In particular, OSM data will be used to estimate the regions.

In summary, the "systemic character" of the project should be emphasised, as only the interconnected consideration of many individual elements makes the turnaround towards a decentralised energy system based entirely on renewable energies possible.

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on the basis of a decision
by the German Bundestag

TrafoKommunE – Transformation process for the municipal energy transition – sector coupled infrastructure and strategies to integrate local actors

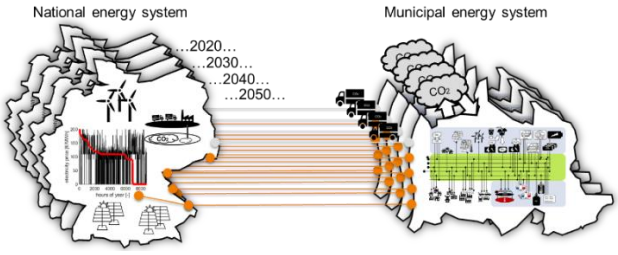
Max Kleinebrahm, Nico Lehmann, Viktor Slednev, Armin Ardone

Partners: DVGW-Forschungsstelle am Engler-Bunte-Institut des KIT, Karlsruhe Institute of Technology (KIT), Gas- und Wärme-Institut Essen e.V., Institut für Ressourceneffizienz und Energiestrategien GmbH, Fraunhofer Institut für System- und Innovationsforschung, MTU Friedrichshafen GmbH, Stadtwerke Karlsruhe GmbH

Funding: Federal Ministry for Economic Affairs and Climate Action (BMWK)

Duration: 2020 to 2023

The cross-sectoral implementation of the energy transition is a major challenge. Municipal suppliers with the involvement of customers as well as local politics and market participants play a central role in this process. The aim of the TrafoKommunE project is, on the one hand, to provide recommendations for action for the cost-effective and timely realisable design of the energy system at the municipal level. On the other hand, possibilities to involve the actors (especially municipal utilities) in shaping the energy transition will be identified. The cross-sectoral approach of this project is intended to show a way in which municipal energy suppliers can guarantee their supply responsibilities for electricity, heat and gas, as well as mobility and digitalisation at reasonable costs. The simultaneous social science investigations take into account the acceptance of citizens and market partners.



Kleinebrahm, M.; Weinand, J.M.; Naber, E.; McKenna, R.;Ardone, A. „Analysing municipal energy system transformations in line with national greenhouse gas reduction strategies, 2023, Applied Energy, Volume 332

With this approach, synergy opportunities and limits of the existing infrastructure and the infrastructure measures necessary for a secure supply until 2050 will be identified and monetarily evaluated. A particular focus of the project is the analysis of the city of Karlsruhe. The tasks of the IIP include, inter alia, the analysis of the current building stock (including its age), appliance equipment, heating types and retrofitting. On this basis, current and future electricity and heating demands for Karlsruhe are estimated. Furthermore, the scenarios developed in the project are quantitatively evaluated with the help of the RE³ASON (Renewable Energies and Energy Efficiency Analysis and System OptimizatioN) model developed at the IIP for the analysis and optimisation of municipal energy systems.

Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

VERMEER – Security of supply in Germany and central Europe during extreme weather situations – The contribution of international power exchange at high shares of renewable energy

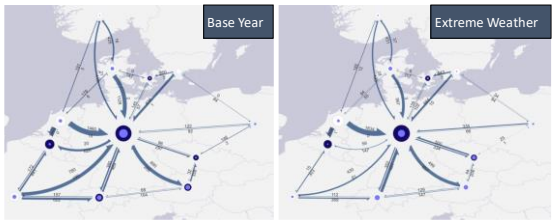
Rafael Finck, Viktor Slednev, Leandra Scharnhorst, Armin Ardone

Partners: Deutsches Zentrum für Luft- und Raumfahrt (DLR), Karlsruher Institut für Technologie (KIT)

Funding: Federal Ministry for Economic Affairs and Climate Action (BMWK)

Duration: 2019 to 2023

The VERMEER project evaluated the consequences of extreme weather events for the security of supply of electricity in Germany, considering the flexibility potential of cross-border electricity trading with regard to weather-dependent transmission grid transfer capacities. For this purpose, several specialized models for defining extreme weather situations, calculating renewable energy generation timeseries, simulating cross-border trading and grid transfer capacities have been further developed and coupled. "Dunkelflauten" or dark doldrums, periods of low combined wind and solar power generation, are projected to increase in the coming century by approximately 11% to 19% according to two climate projection calculations. An in-depth analysis of historical weather patterns (applied to wind and solar generation fleet of the target year of this study – 2035) reveals this for a system as defined in the TYNDP Distributed Energy scenario. During the winter of 1996/1997, the residual load, an indicator of potential under-supply situations like cold dark doldrums, reached notably high levels over a three-month period – but also for shorter periods such as days or weeks. Analyses of the German and neighbouring electricity markets show that within the assumptions based on this scenario extreme weather events such as the examined cold dark doldrums lead to shortages in the German market zone that cannot be compensated by conventional generation or cross-border trading. Trading flows to neighbouring market zones are significantly altered during such events compared to a base case scenario. The simultaneous occurrence of extreme weather across Europe limits the effectiveness of increased transmission capacities in ensuring security of supply, necessitating additional reserve capacities. Regarding power grids, the analyzed extreme situation reduces the occurrence of grid bottlenecks, as they strongly correlate with wind power generation and constitute a weak wind event. However, with increased transmission capacity, the overall amount for redispatch rises; renewable energy curtailment is less affected than conventional power plants. In addition to the market-oriented assessment of security of supply, network simulations indicate that a slight amount of load shedding is necessary in all scenarios to ensure a bottleneck-free operation. The necessary load shedding does not exhibit a significant increase between the base scenario and the extreme situation, nor can it be substantially reduced by increasing transmission capacities. In summary, and contrary to expectations, the expansion of the electricity network does not offer significant additional relief during extreme weather events.



Comparison of cumulated trading flows between the market zones during the extreme weather event in GWh.

Supported by:

Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

VerSEAS – Security of supply in a transformed power system with extreme shares of renewable energies and strong sector coupling

Florian Zimmermann, Thorsten Weiskopf, Emil Kraft

Partner: TU Dresden, Fraunhofer ISI, ESA² GmbH

Funding: Federal Ministry for Economic Affairs and Climate Action (BMWK)

Duration: 07/2020 to 12/2023

VerSEAS

The main objective of the research project "VerSEAS" is to investigate the security of supply in Germany and its neighboring countries in compliance with the Paris climate targets. In order to reduce carbon emissions to a sufficient extent, high shares of renewable energies and, at the same time, a strong sector coupling are required. The focus of the analyses is on the one hand on the interactions and the potential of different flexibility options and on the other hand on possibly needed adjustments of the market design and the regulatory framework to raise this potential. Previous analyses of security of supply in Germany are extended by three main aspects:

- drivers and effects of the diffusion and operation of residential PV battery storage,
- influence of individual decision behavior of investors on the regional diffusion of sector coupling technologies,
- contribution of targeted regional allocation of investments in generation capacity and use of regional flexibilities to security of supply, under consideration of the transmission grid.

The analyses are based on the joint application of the electricity market simulation model PowerACE, the optimal power flow model ELMOD, and the two demand models FORECAST and eLOAD. For this research project, the model portfolio will be extended by a newly developed simulation model for decentralized electricity markets. This model will be integrated into the existing model coupling framework in order to investigate the effects of the nationwide rollout of decentralized markets on the centralized electricity market.

The work at IIP aims to evaluate the effects of individual investment decisions of different actors on the security of supply in an interconnected electricity market with different market designs. For this purpose, the existing agent-based electricity market model PowerACE will be extended with respect to various aspects.

As part of VerSEAS, a public workshop on supply security was planned and held in Stuttgart on September 26, 2022. Compelling presentations from politics, industry and science, which provided insights into the stakeholder-specific positions and served as a starting point for the discussions, were followed by about 80 participants.

The following tasks were carried out in 2023:

- Investigation of the impact of demand side management on the security of supply
- Study of a bidding zone split of Germany
- Release of the PowerACE electricity market model as open-source code

VerSEAS workshop in Stuttgart

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

Awards

Emil Kraft wins EEX Group Excellence Award

Dr. Emil Kraft won the EEX Group Excellence Award for his paper "Stochastic optimization of trading strategies in sequential electricity markets," published in the European Journal of Operational Research. This prize is awarded for outstanding scientific work that deals with current political, regulatory, technical, or economic issues in the areas of energy and agricultural products, as well as their stock exchange trading or sustainability issues.

Completed PhD Dissertations and Habilitations

PhD dissertation: "Techno-economic evaluation of battery storage systems in industry"

Fritz Braeuer

In the context of a changing energy system towards one dominated by renewable energy sources, the demand for flexible energy generation and consumption will increase. Battery storage systems can provide a significant share of this energy flexibility, especially when combined with an industrial manufacturing plant to shift the industrial electricity demand over time. This paper contributes to a better understanding of the business decision when investing in a battery storage system and when marketing energy flexibility. For this purpose, the work considers the techno-economic and regulatory framework for flexibility measures and examines the optimal investment and dispatch planning for a battery storage system in an industrial company.

The studies in this thesis focus on three central aspects. As a first aspect, the various revenue streams for the stored electricity are analysed and how these influence the profitability of a battery storage system. In particular, the provision of frequency containment reserve power, peak load shifting or peak shaving, arbitrage trading on the energy markets and the increase in self-consumption through photovoltaic self-generation are addressed. For this purpose, an optimisation model is formulated as a discrete, linear programme that maps the economic framework of the flexibility markets and integrates the technological constraints of the battery storage system. As a second aspect, uncertainties about market prices, load and generation behaviour are integrated into the optimisation model and the influence on the investment decision is investigated. This is done on the one hand by a two-stage robust optimisation model, which represents the uncertainty about the market success on the intraday market. On the other hand, the significance of the sequence of uncertain market decisions is illuminated through a multi-stage stochastic optimisation model. As a third aspect, the trade-off between the economic and ecological use of a battery storage system is analysed. For this purpose, an ecological, CO_2-minimal dispatch is calculated by deriving national CO_2-emission factors and compared with an economically optimal dispatch.

The case studies are analysed based on real industrial load data from small, medium and large enterprises. The thesis discusses the technical and economic framework conditions, with the main focus on Germany. However, a comparison between the countries Germany, Denmark, and Croatia is also presented,

The results show that peak shaving and the provision of frequency containment reserve are complementary and make the investment in a battery storage system economically viable. Self-generation through a photovoltaic system can reduce the risk arising from uncertain energy market prices. However, the sequence of uncertain decisions has a significant impact on the design of the battery storage system. Economically feasible operation through arbitrage trading, on the other hand, is not possible due to the small price differences in the markets and limitations due to battery ageing and efficiency. These battery characteristics also influence the use of a battery storage system for CO_2-reduction. Due to the limited number of cycles and relatively high charging losses, battery technology is currently unsuitable for CO_2-minimal storage use. Nevertheless, the economic and ecological potential of battery storage systems strongly depends on individual factors such as local grid charges, the selected battery technology and the individual industrial load profile. Advances in battery technology, such as increased lifetime, and possible new flexibility markets, such as dynamic grid charges, offer new application and marketing opportunities that could increase the economic viability of a battery storage system.

PhD dissertation: "The Socio-Technical Dynamics of Renewable Energy Policies in Germany"

Joris Dehler-Holland

Growing environmental concerns and human-caused climate change increase the pressure on policymakers for rapid action to transform how societies convert energy, produce goods, or transport freight. Innovation and technological progress may contribute to such transitions. However, technological change is hard to predict, requires time, and may be laden with political conflicts. Although more sustainable technologies are available, incentivizing demand and deployment are crucial to accelerate transitions. As transformations develop over decades, understanding the temporal dynamics of policies is critical for governance.

In Germany, the renewable energy act incentivizes the deployment of renewable energy technologies by remunerating electricity fed into the common grid. This dissertation assesses how socio-technical developments of solar and wind energy conversion technologies and the renewable energy act interactively shaped each other. Drawing on frameworks such as technological innovation systems, legitimacy, framing, and policy feedback, the contents of 16,485 newspaper articles and additional empirical studies were scrutinized. Combining methods from natural language processing, machine learning, and statistics, this thesis develops text models to assess changes in content and sentiment in large corpora over time. Three studies focus on the shifts in media framing of the German renewable energy act, the underlying co-evolution of technological and policy processes, and the development of the legitimacy of wind power.

The results confirm that renewable energy deployment and policy are contested with varying intensity over time. Where change ought to occur, non-linear dynamics of innovation and technology uptake, growing policy costs, economic interests of incumbents, and technology side effects increasingly complicate policymaking over time. The early phases of the renewable energy act were shaped by positive expectations toward renewable energy technologies, which later shifted towards an emphasis on policy costs. The findings highlight the importance of the prosperity of underlying innovation systems as supporters of policy ambition and maintenance over time. However, policy costs and side effects must be managed effectively to withstand increasing contestation. These results may contribute to advancing the successful governance of sectoral transitions likely to unfold over several decades.

PhD dissertation: "Coupling life cycle assessment with energy system analysis"

Lei Xu

One of the main drivers for switching the current energy system from a conventional fossil-base to one dominated by renewable technologies is climate change. However, energy system transformation aiming at reducing greenhouse gas (GHG) emissions may lead to increases in other types of environmental impacts. Incorporating environmental impacts beyond climate change into future energy systems is required, in order to develop energy policies that do not, or at least can reduce, conflict with other goals.

With this as the background, this thesis couples life cycle assessment (LCA) with energy system analysis, to broaden the scope by including additional environmental impacts, and to switch from a direct emissions perspective to a life cycle perspective. For this purpose, a standard LCA approach is applied to assess energy technologies. Subsequently, the standard LCA is extended to couple with energy system models (ESM) for the assessment of multi-technological energy systems, from both life cycle and energy system perspectives. Considering the methodological challenges that occur due to differences between the models resulting from their different system boundaries, databases, and the levels of detail of their input data, the thesis introduces the Environmental Assessment Framework for Energy System Analysis (EAFESA) as a guideline for studies to cope with model coupling between LCA and ESM.

This thesis includes four papers with different study aims. Paper A applies the standard LCA approach for technological assessment. As wind power is one of the most promising renewable energy sources worldwide, a case study assessing the environmental impacts of wind power technologies is conducted. Paper B develops the EAFESA framework and includes a case study to elaborate how to use the framework. Paper C and Paper D are two additional case studies applying the EAFESA framework for model coupling between LCA and ESM, considering, respectively, one of the two model coupling directions. The applications of the EAFESA framework in the case studies confirms the importance and benefits of "integrated thinking" as proposed by EAFESA, which allows minimizing the pitfalls of combining both models comprehensively. At the same time, EAFESA has the potential to raise awareness of issues not often discussed among policymakers. As shown, for example, the decarbonized electricity system will be accompanied by increased metal demand and urban land occupation. Nevertheless, metal demand could be decreased slightly, together with the decrease of GHG emissions, when the system expenditure increases insignificantly.

PhD dissertation: "Effekte von Kapazitätsmechanismen in gekoppelten Strommärkten"

Florian Zimmermann

The European Union's aim of establishing a single internal market leads to increasing electricity trading capacities between the member states. Furthermore, the share of renewable energy sources in the electricity sector continues to grow. Besides their greenhouse gas neutrality, renewable energies also have low variable operating costs. Due to the merit order effect, these low costs lead to lower revenues for dispatchable power plants.

However, dispatchable power plants remain necessary for a reliable supply in today's electricity system. In order to maintain the reliability of the electricity system, market design mechanisms can help not only remunerate the generated electricity but also the secured capacity and thus ensure revenues for the dispatchable power plants. This dissertation, therefore, presents various market designs. As market design changes are usually unilateral, effects on other markets can arise, which are examined.

An established agent-based electricity market simulation model is extended and applied for the investigations in this dissertation. For this purpose, the geographical framework of the model is enlarged so that 16 European countries can be simulated. In addition, the model is methodologically improved by integrating a long-term price forecast that considers the cross-border effects of implicitly coupled electricity markets for investment decisions. Furthermore, a methodology for determining the hourly dispatch of seasonal storage hydropower plants is integrated into the model. Both are necessary due to the geographical expansion in order to be able to represent the regionally deployed generation technologies or the particular characteristics of the modelled markets.

This dissertation contains four articles, of which one article highlights the theoretical background of market designs and capacity remuneration mechanisms. The remaining three contributions each conduct a case study with a different focus (e. g., analyses of market design options, investment incentives, or cross-border effects).

The results show that energy-only markets (in which only the energy sold is remunerated) are efficient in terms of short-term resource allocation (power plant dispatch), but in the long run, scarcity signals are necessary for investment incentives, but the signals' occurrence is uncertain. Therefore, capacity markets are more beneficial in the long run as they foster continuous investment to ensure generation adequacy. Concerning generation adequacy, in the energy-only market, implementing a strategic reserve can help in the short to medium term, but the reserve is rather inefficient in the long term. The market design and the (resulting) investments can also cause long-term cross-border effects in other countries. A capacity market in one country can lead to falling wholesale electricity prices and thus to unprofitable power plants in neighbouring coupled market areas, which is why investments in power plants in countries with capacity markets are more likely to be incentivized. However, with the further expansion of renewable energies in Europe, dependencies on single large electricity markets, especially regarding price correlations, seem to decrease.

PhD dissertation: "Regionality in Electricity Products – A Residential Consumer Perspective"

Nico Lehmann

In the wake of climate change, many countries around the world have decided to fundamentally change their energy systems and to focus on renewable energy sources. In Germany, this transformation of the energy system has led to the expansion of energy supply from renewables, especially wind and photovoltaics, and an electrification of the demand side. Although the general acceptance of the energy transition among the German population remains high and has recently been pushed by the Russia-Ukraine conflict, local resistances to the construction of new generation facilities are increasing. The reasons for these resistances are manifold and include economic concerns, immissions (e.g., noise pollution), and visual impairments. From a technical perspective, the expansion of renewable energies and the electrification of energy demand not only pose the challenge of balancing electricity generation and supply, but can also lead to temporary and local grid congestions, caused by, for example, reversed load flows, excess feed in, and high simultaneities in electricity consumption.

Regional electricity products, i.e., products that consider the location of electricity generation and consumption, may help to address these challenges. This thesis investigates two types of regional electricity products from a consumer perspective: (i) First, regional electricity tariffs, i.e., traditional electricity tariffs with generation from regional generation facilities and (ii) second, quota schemes, a novel type of demand response (DR) program. If properly designed, these products may help to, inter alia, increase consumers' acceptance of generation facilities and enhance security of supply by incentivizing flexibility for grid relief. To date, however, little is known about consumers' preferences and their underlying motivations regarding these regional electricity products.

For this reason, the thesis at hand presents four empirical data sets in five studies to shed more light on the preferences and motivations of German household consumers for regional electricity tariffs and quota schemes. More specifically, three studies are dedicated to regional electricity tariffs and examine consumers' preferences and willingness to pay (WTP) for electricity supply specifically from their region. The other two studies focus on DR quota schemes, i.e., on consumers' willingness to participate in such programs and what they value most in their design. All studies use either data from choice experiments, data on consumer motivations, or both. In doing so, the studies not only apply methods from the fields of behavioral economics and environmental psychology to an energy context, but also use sophisticated and new model specifications that have not been employed before.

Overall, the results of all studies show that the preferences and motivations of German household consumers are heterogeneous, with respect to both regional electricity tariffs and quota schemes. This confirms that the two regional electricity products under investigation will not be willingly adopted by every household consumer. Rather, regional electricity products should – wherever possible – be tailored to individual preferences and address underlying consumer motivations. For example, results show that consumers' WTP is not primarily and exclusively driven by environmental motivations. Likewise, and contrary to popular belief, emphasizing the financial benefits of DR quota schemes is not as effective as emphasizing the environmental benefits to push consumers' willingness to participate. However, it is important to keep in mind that some consumers may not be willing to pay for regional electricity at all, or may not be motivated to participate in DR programs, irrespective of the benefits they bring about. This not only calls into question the economic viability of the two regional electricity products, as additional costs on the procurement and sales side may not be covered, but also the technical viability in the case of quota schemes if the number of participating consumers is too small to effectively address grid congestions. The five studies of this thesis provide important insights for practitioners and policy makers aiming to establish these regional electricity products among consumer groups. Applying these insights in practice may help to advance the sustainable energy transition in ways that are acceptable and feasible for energy consumers.

PhD dissertation: "Gebäudespezifische Simulation und Validierung von Stromlastprofilen für Wohn- und Nichtwohngebäude zur Anwendung in der energetischen Quartiersplanung"

Sally Köhler

The building sector and energy supply hold a high potential for the reduction of greenhouse gas and CO2 emissions. In order to utilize the potential of this complex and multifaceted topic, tools are required that are capable of modelling the existing building stock in terms of energy and analysing alternative energy supply options. To ensure that the results of such tools are incorporated into the planning processes of municipalities and cities on a practical level, it is important to include local conditions and techno-economic aspects in the planning scenarios. The question of prioritizing measures and selecting buildings to start with is particularly important in the implementation process.

This dissertation focuses on the development of a tool that enables energy analyses at the building level in the context of neighbourhood planning. The emphasis lies on the simulation of building-specific electricity load profiles for residential and non-residential buildings using 3D models. Statistical and heuristic methods (greedy algorithms) are used to enhance the 3D building models with households and occupants. The annual electricity demand is determined based on the household area and the number of occupants. This demand is distributed to time units using frequency density functions based on measured data with defined class intervals. By applying a pseudo-random number generator, the initial value is determined. The electricity load profiles are generated by a Markov chain which, depending on the class interval which is chosen, generates an updated frequency density function for the next time step based on the measured values of the corresponding class interval. For non-residential buildings, a hierarchical building usage library is developed that assigns standard load profiles to approximately 200 usage types using ALKIS codes. The annual electricity demand is determined based on area-specific electricity indicators and distributed to the load characteristics of the standard profiles. Measures and metrics from descriptive statistics, time series analysis, and graph-based techniques for determining similarity to measured data are applied to validate the developed methods. These are complemented by complexity measures of fractal dimension, number of local maxima, and length of the curve.

The developed methods are integrated into the simulation platform SimStadt. The validation of the method for assigning households and occupants to 3D models is performed on the basis of three case studies. At the county and city levels, respectively, the method shows deviations of -6% to +7% in the number of households and of -13% to +8% in the number of occupants compared to official statistics. The comparison of the synthetically generated electricity load profiles with measured data and synthetic data of two existing electricity load profile generators shows that the implemented method is able to reproduce typical characteristics of electricity load profiles. The fractal dimension proves to be a suitable measure for evaluating the complexity of electricity load profiles. For the electricity load profiles of non-residential buildings, a comparison with existing measured data is also performed. The deviations on city level are between -19% and +1% for three investigated non-residential building use types. The generated electricity load profiles for residential buildings are also applied in two case studies for neighbourhood energy planning. The first case study focuses on the optimal energy design of a neighbourhood with centralized and decentralized energy system options. It is shown that the optimal ratio of centralized to decentralized options is 2 to 1 and a cost-optimal reduction in heat demand is achieved at about 20%. The cost optimum for locally generated electricity is achieved by combining PV systems, electricity from the grid and from local CHP plants in a ratio of 1 to 1 to 2. In the second case study, the electricity load profiles are used to size residential PV battery systems. Here, the building-specific SLP data are particularly important for determining the self-consumption fraction and for further economic analysis.

Overall, the developed methods and the SimStadt-tool provide a valuable framework for building-level energy analysis and urban planning. They enable the consideration of local conditions and techno-economic aspects, and offer insights into energy demand patterns and alternative energy supply

options. However, further research and validation with larger datasets are needed to improve the accuracy and reliability of the methods and to ensure their applicability in various urban contexts.

PhD dissertation: "Kopplung der Sektoren Strom und Gas mittels Power-to-Gas-Anlagen zur Dekarbonisierung der Stromversorgung"

Christoph Nolden

In order to achieve the climate protection goals, greenhouse gas emissions must be reduced as quickly as possible. The power sector (including public heat production) plays an important role. On the one hand, it is responsible for around a third of energy-related greenhouse gas emissions and, on the other hand, other sectors can be decarbonized by electrification. Important key technologies are heat pumps and electrolysers for the production of hydrogen.

The Renewable Energy Sources Act stipulates that the share of renewable energies in gross electricity consumption should grow to at least 65 percent by 2030 and that before 2050 the entire amount of electricity in the Federal Republic of Germany has to be generated greenhouse gas neutrally. The coalition agreement of the incumbent federal government also stipulates that the renewable energy target must be geared towards increased gross electricity demand and that the share of renewable energies should already be 80 percent by 2030.

In order to achieve the stated goals, renewable energy expansions must be accelerated. In addition to greater flexibility in electricity demand, renewable energy expansion requires a significant increase of storage options in order to ensure security of supply in times of low renewable electricity production and to avoid curtailments in times of very high renewable electricity production. Beside battery storages, the power-to-gas concept should be considered for two reasons. On the one hand, it meets the requirements for short-term storage as well as seasonal long-term storage. On the other hand, the amounts of hydrogen produced can be used to convert electricity back into electricity or can replace the use of fossil fuels in other sectors.

This work analyses the extent to which the integration of electrolysers into the electricity supply system has a positive effect on the ability to integrate fluctuating renewable energies. The focus is on three questions:

1. How many power-to-gas systems can be integrated into the system from an economic point of view based on expansion goals?
2. How does this integration affect the curtailments of renewable energies and how can this effect be quantified?
3. To what extent can the power sector be completely converted to renewable energies and decarbonized through the power-to-gas concept?

To address the questions, a techno-economic optimisation model is used, which is formulated as a mixed-integer problem. It maps the German electricity supply system with all power plants and the transmission network in high spatial resolution. All decision relevant expenses are included in the objective function. The important model variables include the expansion and dismantling of conventional power plants, the addition of electrolysers and the curtailment of renewable energies. The load flows that occur in the high-voltage network are determined endogenously and their technical permissibility is ensured via additional conditions.

The analysis is based on three scenarios. In the base scenario, the development of the system is considered without the integration of electrolysers. In the second scenario, a renewable expansion target of 80 percent by 2050 is set and the model can add power-to-gas systems to certain network nodes. The third includes, as an additional constraint, that the electricity demand is completely covered by renewable energies and assumes the necessary expansion path for renewable energies.

The results show that in the second scenario, power-to-gas plants with an installed capacity of around 5 GW_{el} are integrated into the system. The curtailment of photovoltaic panels and wind turbines can thus be reduced by a third from 9 per cent to 6 per cent. With a significantly higher expansion corridor for renewable energies (scenario three), the installed capacity of power-to-gas plants increases to approx. 38 GW_{el} in the same observation period. The amount of hydrogen produced in these plants is sufficient for

reconversion into electricity and for substituting conventional natural gas in other sectors, resulting in a CO_2 reduction of around 4 million tonnes per year. This work shows that the power-to-gas concept can make a significant contribution to the complete decarbonisation of the electricity supply. It is fundamentally suitable for utilising surpluses in times of high feed-in from renewable energies for energy storage and for reconverting the stored energy into electricity in times of low availability of renewable plants. It also has a positive effect on the integration capability of renewable energies by helping to reduce and avoid curtailment.

Overall, the market environment and the political framework conditions are very dynamic. On the one hand, the direct demand for hydrogen expected in the meantime, which is not considered in this study, represents a further driver for the integration of electrolysers. On the other hand, the question of the design of funding instruments for the ramp-up of a hydrogen economy is still open. Both have a direct impact on the results of this study. Nevertheless, the results can be used for further subsequent analyses and investigations.

Staff as of December 2023

Head of the Chair of Energy Economics

Prof. Dr. Wolf Fichtner

Administrative Staff

Michaela Gantner-Müller

Corinna Feiler (also working for the Chair of Business Administration, Production and Operations Management)

Josiane Folk (also working for the Chair of Business Administration, Production and Operations Management)

Liana Blecker (also working for the Chair of Business Administration, Production and Operations Management)

Heads of Research Groups

M. Sc. Rafael Finck – Sustainable Infrastructures for Renewable Energy Systems

M. Sc. Max Kleinebrahm – Energy Demand and Mobility

Dr. rer. pol. Armin Ardone, M. Sc. Viktor Slednev – Sustainable Energy Markets & Future Energy Commodities

Dr. Daniel Sloot – Energy and Behavior

Postdocs & Doctoral Researchers and their research-topics

Nora Baumgartner: Elaboration of factors influencing the user acceptance of V2G charging.

Julius Beranek: A Techno-Economic Evaluation of Large-Scale Battery Storage Systems.

Anthony Britto: The diffusion of energy-efficiency technology: process and policy.

Thomas Dengiz: Development of algorithms for demand side management of residential buildings using methods from the field of multi-objective optimization and machine learning.

Rafael Fink: Analysis of the impacts of increasing generation from renewable sources in the European electricity market on transmission grids considering flow-based market coupling.

Wenxuan Hu: Assessment of different design options for the European electricity market and their impacts on various national energy markets.

Max Kleinebrahm: Future residential energy system design.

Uwe Langenmayr: Looking at the supply site of synthetic energy carriers: A global perspective on production and transportation

Christian Perau: Sector coupling of electricity and gas infrastructure with focus on hydrogen production and transmission.

Alexander Plarre: Investigation of the European emission trading system under

consideration of emission abatement technologies.

Thorben Sandmeier: Analysis of the economic and technical benefits of an increased use of flexible network elements in electrical transmission grids.

Leandra Scharnhorst: Socio empirical research on consumer behavior and techno-economic assessment of future European industrial.

Johannes Schuhmacher: Household Flexibility and Disruptive Events in Electricity Markets.

Julia Schuler: Techno-economic assessment of hydrogen, hydrogen derivatives and metals as energy carriers.

Tim Signer: Analysis of vehicle-to-grid technology and market integration through agent-based electricity market analysis.

Viktor Slednev: Integrated energy conversion, storage and transmission modelling in large-scale multi-energy systems with a high RES share.

Stephanie Stumpf: Analysis of factors and dynamics influencing household's renewable energy technology adoption.

Thorsten Weiskopf: Investigation of RES-support schemes in connected European electricity markets.

International Collaboration

Location: University of Auckland, Auckland, New Zealand

Who: Thomas Dengiz

Host: Associate Professor Andrea Raith, Department of Engineering Science

Period: February to May 2023

Short description of stay: Financed via the Karlsruhe House of Young Scientists (KHYS) Research Travel Grant, Thomas Dengiz spent 3 months at the Department of Engineering Science at the University of Auckland. Together with his supervisor, Andrea Raith, he worked on multiobjective optimization for demand side management in residential areas. The goal was to develop a novel pareto-local-search approach to find good trade-off solutions for the objectives of minimizing electricity costs, minimizing the peak load in the local grid and maximizing the inhabitants' thermal comfort. The developed approach is compared to both exact methods for multiobjective optimization and metaheuristic methods. The results reveal that the novel pareto-local-search method outperform known metaheuristic approaches and yields a good trade-off between quality of the results and runtime. It is planned to use and further develop the approach within the *ASIMUTE* project.

Location: Evans School of Public Policy and Governance, University of Washington, Seattle, United States

Who: Daniel Sloot

Host: Prof. Dr. Ann Bostrom, Weyerhaeuser Endowed Professor in Environmental Policy

Period: January to April 2023

Short description of stay: Daniel Sloot spent four months as a visiting researcher at the Evans School of Public Policy and Governance. The aim of the research visit was to develop a new field of research on the societal acceptance of negative emissions technology. Together with hosting professor Ann Bostrom, he explored the public support for direct air capture in relation to the moral hazard issue – the potential risk that the availability of negative emissions technologies could be seen as undermining mitigation efforts and thus be avoided by policy makers. They conducted an empirical study among a nationally representative sample of the U.S. population. Next to the research activities, Daniel Sloot gave two guest lectures at the hosting institution, on the issue of moral hazard and negative emissions technologies, as well as on other research examining demand response in private households. The research stay was financially supported by a Research Travel Grant from the Karlsruhe House of Young Scientists (KHYS).

Location: NTNU Trondheim, Trondheim

Who: Anthony Britto

Host: Stein-Erik Fleten

Period: April – July 2023

Short description of stay: Anthony Britto spent three months as a visiting researcher at the Department of Industrial Economics and Technology Management at NTNU Trondheim. The objective of the research was to develop a real options model for residential energy-efficiency investments, with a focus on household

wealth and energy price uncertainty influencing energy consumption and investment decisions. Research activities have since continued, with plans for several forthcoming publications. The research stay proved fruitful, fostering scientific collaboration and strengthening ties between the IIP and the operations research group at NTNU. New connections were established, particularly with Prof. Carlos Oliveira, an expert in mathematical optimization. The research stay was financially supported by a Research Travel Grant from the Karlsruhe House of Young Scientists (KHYS).

Teaching Activities

The Chair of Energy Economics offers several modules in the fields of energy economics, energy markets and technology. For undergraduate students, the module "Energy Economics" contains three lectures. Moreover, the chair offers nine courses in the context of the two master modules "Energy Economics and Energy Markets" and "Energy Economics and Technology". Furthermore, the chair offers several seminars in energy economics where current developments are addressed. The chair supervises on average about 70 bachelor's and master's theses per year.

Introduction to Energy Economics ~110 students

Prof. Dr. rer. pol. W. Fichtner
Dr. rer. pol. A. Ardone
M. Sc. N. Lehmann
M. Sc. T. Sandmeier

This lecture aims to make students familiar with basic concepts of energy economics. The main contents are the different energy carriers' gas, oil, coal, lignite and uranium. The terms of reserve and resource as well as associated technologies are introduced. Subsequently, the final carrier electricity and heat are introduced and other forms of final energy carriers (cooling energy, hydrogen and compressed air) are presented. The lecture aims to enable the students to characterize and evaluate the different energy carriers and their peculiarities and conveys a fundamental understanding of contexts related to energy economics.

Renewable Energy – Resources, Technologies and Economics ~105 students

PD Dr. rer. pol. P. Jochem

This lecture introduces the basics of renewable energies starting with a general introduction on the global situation and the energy balance of the earth followed by the different renewable forms hydro, wind, solar, biomass and geothermal. The promotional concepts of renewable energies are presented and the interactions in the systemic context are examined. The course includes an excursion to the "Energieberg" in Mühlburg.

Energy Policy ~35 students

Apl. Prof. Dr. rer. pol. M. Wietschel
M. Sc. Nora Baumgartner

This course deals with material and energy policy of policy makers and includes the effects of policies on the economy as well as the involvement of industrial and other stakeholders in policy design. At the beginning, neoclassical environment policy is discussed. Afterwards, the concept of sustainable development is presented and strategies how to translate this concept into policy decision follows. In the subsequent part of the course, an overview of the different environmental policy instruments, classes, evaluation criteria for these instruments and examples of environmental instruments like taxes or certificates is discussed. The final part deals with implementation strategies of material and energy policy.

Liberalised Power Markets ~50 students

Prof. Dr. rer. pol. W. Fichtner
Dr. rer. pol. E. Kraft
M. Sc. T. Signer
M. Sc. J. Beranek

After presenting the liberalisation process in the European energy market, this course examines pricing and investment mechanisms in liberalised power markets. The power market and the corresponding submarkets are discussed. Moreover, the course deals with the concept of risk management and market power in liberalised energy markets. It concludes different market structures in the value chain of the power sector.

Energy Trading and Risk Management ~30 students

Dr. rer. pol. E. Kraft
Prof. Dr. rer. pol. W. Fichtner

This lecture on energy trading introduces the major energy carrier markets such as gas, oil or coal. Different pricing mechanisms are discussed. In terms of methods, evaluation techniques from financial

mathematics and key risk analysis approaches are presented.

Simulation Game in Energy Economics ~15 students
Dr. rer. pol. M. Genoese
M. Sc. F. Zimmermann

This course is structured in a theoretical and a practical part. In the theoretical part, the students are taught the basics to carry out simulations themselves in the practical part which comprises amongst others the simulation of the power exchange. The participants of the simulation game take a role as a power trader in the power market. Based on various sources of information (e.g., prognosis of power prices, available power plants, fuel prices), they can launch bids in the power exchange.

Quantitative Methods in Energy Economics ~10 students
Dr. rer. nat. P. Plötz
Dr.-Ing. T. Dengiz
Dr.-Ing. H. Ü. Yilmaz

Energy economics makes use of many quantitative methods in the exploration and analysis of data as well as in simulations and modelling. This lecture course aims at introducing students of energy economics to the application of quantitative methods and techniques as taught in elementary courses to real problems in energy economics. The focus is mainly on regression, simulation, time series analysis and related statistical methods as applied in energy economics.

Heat Economy ~20 students
Prof. Dr. rer. pol. W. Fichtner
Dr.-Ing. T. Dengiz
M. Sc. S. Stumpf

After introducing the principle of heat economics, this lecture provides insights into CHP technologies and heat systems including profitability calculations. Further, the distribution of heat, the demand for space heating as well as thermal insulation measures and possibilities for heat storage are highlighted. The legal framework conditions for heat economy conclude the theoretical part of the lecture. A laboratory experiment with a compression heat pump gives the students the opportunity to apply the acquired theoretical knowledge.

Energy Systems Analysis ~15 students
Dr. rer. pol. A. Ardone
Dr.-Ing. T. Dengiz
Dr.-Ing. H. Ü. Yilmaz

This lecture gives an overview of different system modelling approaches for energy system modelling. Scenario techniques are introduced, the concept of unit commitment of power plants and interdependencies in energy economics are examined. Scenario-based decision making in the energy sector is highlighted and insights into visualisation and GIS techniques for decision support in the energy sector are given. In computer exercises, the basics of the modelling language GAMS are taught. The students use the modelling language to define optimisation problems for answering simple energy related research questions.

(Smart) Energy Infrastructure ~30 students
Dr. rer. pol. A. Ardone
Prof. Dr. Dr. A. M. Pustisek

This lecture provides insights into the topic of infrastructures for energy transport, particularly the transport of natural gas and electricity, and the underlying economics. In the field of energy infrastructure, the keyword "smart" is becoming increasingly important. The lecture treats concepts of smart electricity transmission, as well as future infrastructure challenges in an energy system with an increasing share of renewable electricity generation. In the field of gas, possibilities for transportation and storage of natural gas are discussed.

Efficient Energy Systems and Electric Mobility ~25 students
PD Dr. rer. pol. P. Jochem

This lecture series combines two of the most central topics in the field of energy economics at present, namely energy efficiency and electric mobility. The objective of the lecture is to provide an introduction to and overview of these two subject areas, including theoretical as well as practical aspects, such as the technologies, political framework conditions and

broader implications of these for national and international energy systems. The energy efficiency part of the lecture provides an introduction to the concept of energy efficiency, the means of affecting it and the relevant framework conditions. Further insights into economy-wide measurements of energy efficiency and associated difficulties are given with recourse to several practical examples. The problems associated with market failures in this area are also highlighted, including the rebound effect. Finally, and by way of an outlook, perspectives for energy efficiency in diverse economic sectors are examined. The electric mobility part of the lecture examines all relevant issues associated with an increased penetration of electric vehicles including their technology, their impact on the electricity system (power plants and grid), their environmental impact as well as their optimal integration in the future private electricity demand (i.e., smart grids and V2G). Besides technical aspects, the user acceptance and behavioural aspects are also discussed.

Energy and Environment ~135 students

Apl. Prof. Dr. rer. nat. U. Karl
M. Sc. U. Langenmayr

This lecture examines the environmental impacts of fossil fuel conversion and related assessment methods. After introducing the fundamentals of energy conversion, the focus is set on air pollution and conversion efficiency. Assessment methods include life cycle assessment of selected energy systems, integrated assessment models, cost-effectiveness analyses and cost-benefit analyses.

Industrial Business Administration ~180 students

Prof. Dr. rer. pol. W. Fichtner
M. Sc. L. Scharnhorst
M. Sc. J. Schuler

In this lecture, students from various fields of study are given an introduction to industrial business administration. Topics from the areas of legal forms, financing, management, cost accounting, investment accounting, optimization, marketing, project management and technology acceptance are presented.

Teaching at the Chair of Energy Economics

Bachelor Module „Energy Economics"

- Introduction to Energy Economics (SS, 5.5 ECTS)
- Renewable Energy – Resources, Technologies and Economics (WS, 3.5 ECTS)
- Energy Policy (SS, 3.5 ECTS)

Master Module „Energy Economics and Energy Markets"

- Liberalised Power Markets (WS, 3 ECTS)
- Energy Trading and Risk Management (SS, 3 ECTS)
- Simulation Game in Energy Economics (SS, 3 ECTS)
- Quantitative Methods in Energy Economics (WS, 3 ECTS)

Master Module „Energy Economics and Technology"

- Efficient Energy Systems and Electric Mobility (SS, 3.5 ECTS)
- Energy and Environment (SS, 4.5 ECTS)
- Energy Systems Analysis (WS, 3 ECTS)
- Heat Economy (SS, 3 ECTS)
- (Smart) Energy Infrastructure (WS, 3 ECTS)

Industrial Business Administration (WS, 3 ECTS)

Publications

University Publications

Braeuer, F. (2023). *Techno-economic evaluation of battery storage systems in industry* [Dissertation, Karlsruher Institut für Technologie (KIT)]. https://doi.org/10.5445/IR/1000157261

Dehler-Holland, J. (2023). *The socio-technical dynamics of renewable energy policies in germany* [Dissertation, Karlsruher Institut für Technologie (KIT)]. https://doi.org/10.5445/IR/1000158922

Köhler, S. (2023). *Gebäudespezifische Simulation und Validierung von Stromlastprofilen für Wohn- und Nichtwohngebäude zur Anwendung in der energetischen Quartiersplanung* [Dissertation, Karlsruher Institut für Technologie (KIT)].

Lehmann, N. (2023). *Regionality in electricity products – a residential consumer perspective* [Dissertation, Karlsruher Institut für Technologie (KIT)]. https://doi.org/10.5445/IR/1000156496 https://publikationen.bibliothek.kit.edu/1000156496

Nolden, C. (2023). *Kopplung der Sektoren Strom und Gas mittels Power-to-Gas-Anlagen zur Dekarbonisierung der Stromversorgung* [Dissertation, Karlsruher Institut für Technologie (KIT)]. https://doi.org/10.5445/IR/1000164346

Xu, L. (2023). *Coupling life cycle assessment with energy system analysis* [Dissertation, Karlsruher Institut für Technologie (KIT)]. https://doi.org/10.5445/IR/1000157936

Zimmermann, F. (2023). *Effekte von Kapazitätsmechanismen in gekoppelten Strommärkten* [Dissertation, Karlsruher Institut für Technologie (KIT)].

Peer-Reviewed Journals

Baumgartner, N., Weyer, K., Eckmann, L., & Fichtner, W. (2023). How to integrate users into smart charging – A critical and systematic review. *Energy Research & Social Science*, *100*, 103113. https://doi.org/10.1016/j.erss.2023.103113

Bülte, C., Kleinebrahm, M., Yilmaz, H. Ü., & Gómez-Romero, J. (2023). Multivariate time series imputation for energy data using neural networks. *Energy and AI*, *13*, 100239. https://doi.org/10.1016/j.egyai.2023.100239

Frahm, M., Dengiz, T., Zwickel, P., Maaß, H., Matthes, J., & Hagenmeyer, V. (2023). Occupant-oriented demand response with multi-zone thermal building control. *Applied Energy*, *347*, 121454. https://doi.org/10.1016/j.apenergy.2023.121454

Fraunholz, C., Miskiw, K. K., Kraft, E., Fichtner, W., & Weber, C. (2023). On the Role of Risk Aversion and Market Design in Capacity Expansion Planning. *The Energy Journal*, *44*(3), 111–138. https://doi.org/10.5547/01956574.44.2.cfra

Kleinebrahm, M., Weinand, J. M., Naber, E., McKenna, R., & Ardone, A. (2023). Analysing municipal energy system transformations in line with national greenhouse gas reduction strategies. *Applied Energy*, *332*, 120515. https://doi.org/10.1016/j.apenergy.2022.120515

Kleinebrahm, M., Weinand, J. M., Naber, E., McKenna, R., Ardone, A., & Fichtner, W. (2023). Two million European single-family homes could abandon the grid by 2050. *Joule*, *7*(11), 2485–2510. https://doi.org/10.1016/j.joule.2023.09.012

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Zimmermann, F., & Keles, D. (2023). State or market: Investments in new nuclear power plants in France and their domestic and cross-border effects. *Energy Policy*, *173*, 113403. https://doi.org/10.1016/j.enpol.2022.113403

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Beranek, J., Kraft, E., & Zimmermann, F. (2023). *Einsatz von Strommarktmodellen zur Untersuchung der Versorgungssicherheit in Europa*. 13. Internationale Energiewirtschaftstagung (IEWT), Wien, Österreich. https://doi.org/10.5445/IR/1000156859

Kraft, E., Miskiw, K. K., & Fleten, S.-E. (2023). *Effects of price-making and portfolio size in stochastic optimization of trading in sequential electricity markets*. 13. Internationale Energiewirtschaftstagung (IEWT), Wien, Österreich. https://doi.org/10.5445/IR/1000157695

Perau, C. (2023). *Impact of spatial electrolyzer allocation in the central european energy system*. International Conference on Operations Research (OR), Hamburg, Deutschland. https://doi.org/10.5445/IR/1000165192

Ruppert, M., Baumgartner, N., Märtz, A., & Signer, T. (2023). Impact of V2G flexibility on congestion management in the german transmission grid. *Driving the Transition to E-Mobility*. 36th international electric vehicle symposium and exhibition, Sacramento, CA, USA. https://doi.org/10.5445/IR/1000161550

Sandmeier, T., Scharnhorst, L., Ardone, A., & Fichtner, W. (2023). *Inducing energy and CO_2 savings in private households by introducing CO_2-budgets – findings from a living lab experiment*. Helmholtz Energy Conference, Koblenz, Deutschland. https://doi.org/10.5445/IR/1000159468

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Scharnhorst, L., Sandmeier, T., Ardone, A., & Fichtner, W. (2023). Incentivized energy consumption adaption in private households facing the energy crisis. *Conference Proceedings - BEHAVE 2023 the 7th European Conference on Behaviour Change for Energy Efficiency*, 668–679. https://doi.org/10.5445/IR/1000165136

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Weiskopf, T., Zimmermann, F., & Kraft, E. (2023). *The long-term impact of increased fossil fuel prices and market design on the market values of renewable generation*. 18th IAEE European Conference „The Global Energy Transition Toward Decarbonization ", Mailand, Italien. https://doi.org/10.5445/IR/1000162308

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Fuchs, S., & Kleinebrahm, M. (Regisseure). (2023). *„Ein teurer Irrweg" – KIT Studie zeigt: Energieautarke Eigenheime sind keine Strategie für die Energiewende in Europa—Campus-Report am 26.12.2023* (Bd. 1141) [Audio & Video]. https://doi.org/10.5445/IR/1000166059

Heinzmann, P., Glöser-Chahoud, S., Schultmann, F., Langenmayr, U., Ruppert, M., Fichtner, W., Arnold, U., Dahmen, N., Fuchs, C., Lam, H., Graf, D., Rauch, R., Haas-Santo, K., Dittmeyer, R., Weyhing, T., Wagner, U., Andresh, M., Haase, M., Patyk, A., … Sauer, J. (2023). *Ergebnisbericht reFuels – Kraftstoffe neu denken* [Forschungsbericht]. Karlsruher Institut für Technologie (KIT). https://doi.org/10.5445/IR/1000159935

Jansen, E., Schuler, J., Ardone, A., Slednev, V., Fichtner, W., & Pfetsch, M. E. (2023). *Global logistics of an iron-based energy network: A case study of retrofitting german coal power plants* (Working Paper Series in Production and Energy 70). Karlsruher Institut für Technologie (KIT). https://doi.org/10.5445/IR/1000158253

Karlsruhe Institute of Technology (KIT), Institute of Industrial Production (IIP), Chair of Energy Economics. (2023). *PowerACE - an agent-based energy market model* (Forschungsdaten KITopen-ID: 1000165932) [Software]. https://gitlab.kit.edu/kit/iip/opensource/powerace

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Zachmann, G., & Heinzmann, P. (Regisseure). (2023). *E-Fuels – Retter der Verbrennungsmotoren? Ein Faktencheck* (Bd. 5). https://doi.org/10.5445/IR/1000165313

Hertzstraße 16 | D-76187 Karlsruhe | phone +49 721 608 44460/44569 | fax +49 721 608 44682 | iip.kit.edu | info@iip.kit.edu