Karlsruhe Institute of Technology

Institute for Industrial Production

Annual Report 2020

Chair of Energy Economics

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Preface

This fourth 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 2020. The four research groups "Distributed Energy Systems and Networks", "Energy Markets and Energy Systems Analysis", "Energy Policy", 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 30 research and 4 administrative staff.

[1]

During 2020, we worked on around 15 ongoing national and international research projects and started about 5 new projects. We published around 20 peer-reviewed journal articles. Furthermore, 1 habilitation was accepted, 2 PhD were completed and 4 theses were defended.

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

[1] Disclaimer: this picture has been taken in 2019. All following pictures have been taken considering the infection protection laws at the time.

Distributed Energy Systems and Networks Group

Head of research group: Dr. Armin Ardone

Members of the research group (fltr): Armin Ardone, Daniel Sloot, Max Kleinebrahm, Nico Lehmann, Leandra Scharnhorst, Rafael Finck, Viktor Slednev, Jann Weinand, Thorben Sandmeier.

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: Christoph Fraunholz

Members of the research group (fltr): Emil Kraft, Christoph Fraunholz, Daniel Fett, Florian Zimmermann. Missing in the picture: Kim Miskiw, Malin Lange.

The sustainable design of 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 goal of the research group *Energy Markets and Energy System Analysis (EMESA)* is the formulation and application of mathematical models to

analyse the implications of political and economic framework conditions as well as technological trends onto the future development of energy systems.

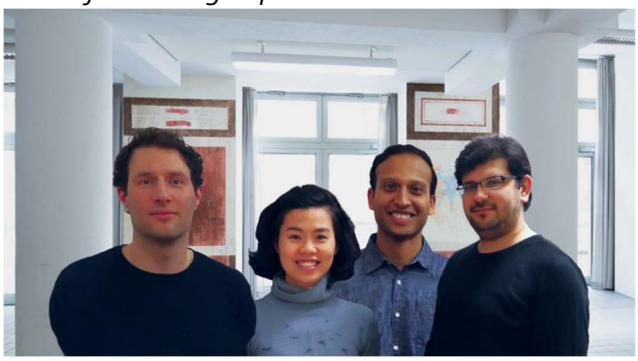
The main research topics include

- market design,
- investments in flexibility options,
- diffusion of energy storage and its impact on the electricity market,
- decarbonisation of the energy sector,
- sector coupling and
- price forecasting and analyses.

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 model-based analyses of the research group EMESA are decision-makers from politics, business and industry.

Energy Policy Group

Head of research group: Joris Dehler-Holland



Members of the group (fltr): Joris Dehler-Holland, Phuong Minh Khuong, Anthony Britto, Hasan Ümitcan Yilmaz

Achieving ambitious climate protection targets requires extensive social, economic and technological change. Due to high greenhouse gas emissions, the energy sector is particularly challenged. Political decision-makers have various tools at their disposal to stimulate sustainable change.

The focus of the Energy Policy Research Group is on policy measures to promote or sanction energy technologies and their economic and societal impacts. Since policy instruments do not emerge independently from political actors, the research group focuses on political processes and their influence on policy measures. Statistical methods for data analysis and economic models are used, but also surveys on the acceptance of technologies.

Transport and Energy Group

Head of research group: Manuel Ruppert

Members of the research group (fltr): Christian Perau, Zongfei Wang, Nora Baumgartner, Sabrina Ried, Manuel Ruppert, Alexandra Märtz, Thomas Dengiz, Uwe Langenmayr.

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. Third, mobility patterns, user behaviour and user acceptance analyses of (technological) innovations in the transportation sector are performed. For answering the 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. These models are applied in different fields from service science and psychology to decentralised electricity systems and electricity markets. Service-related topics in our field of research are allocated to our associated eMobility Lab at the Karlsruhe Service Research Institute (KSRI). We have a comprehensive exchange with international partners from academia and industry. The funding comes from various research projects for German ministries, German Research Foundation (DFG), the European Commission, Helmholtz Association, local ministries, and industry.

Research Projects

BDL – Bidirectional Charging Management

Katrin Seddig, Sabrina Ried, Fritz Braeuer, Nora Baumgartner, Kira Schumacher

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

Funding: Federal Ministry for Economic Affairs and Energy (BMWi)

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 with 50 BMW i3. The flexibility and storage capacity of electric vehicles (EVs) should be optimally integrated 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. To this end, existing energy system models are applied and extended to research the effects of V2G on the European electricity market. In addition, the potential of V2G for improved integration of renewable energies has been analysed based on a grid model. 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, surveys were conducted on the user acceptance of a possible design of EV's planned charging control by distributed system operators (§14a EnWG).
Another topic that is dealt with in the context of user acceptance research relates to tariff design and determination of the willingness to pay for controlled charging management tariffs.

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C/sells: The Future Energy System in the Solar Arc of Southern Germany. A Project within the Support Programme "Smart Energy Showcases - Digital Agenda for the Energy Transition (SINTEG)"

Armin Ardone, Dogan Keles, Manuel Ruppert, Nico Lehmann, Emil Kraft, Sabrina Ried

Partners: 56 partners, among them: Industrial partners: DB Energie GmbH, devolo AG, EAM GmbH & Co. KG, Flughafen Stuttgart GmbH (Stuttgart Airport), MVV Energie AG, Netze Mittelbaden GmbH, Next Kraftwerke GmbH, Power Plus Communications AG, Seven2one Informationssysteme GmbH, Stadtwerke München Services GmbH, TenneT TSO GmbH, TransnetBW GmbH.

Academic partners: Deutsches Zentrum für Luft- und Raumfahrt (DLR), FfE Forschungsstelle für Energiewirtschaft e.V., Fraunhofer IAO, Fraunhofer ISE, Fraunhofer ISI, FZI Forschungszentrum Informatik, Hochschule Offenburg, Hochschule Ulm, International Solar Energy Research Center Konstanz, TU München, Universität Stuttgart.

Funding: Federal Ministry for Economic Affairs and Energy

Duration: 2017 to 2020

C/sells intended to create a cellular structured energy system. Geographically limited technical solutions ("Cells") were developed which were the core of the project. The supply, use, distribution, storage and other infrastructure services within the individual cells, e.g. properties, districts and cities, are optimized mostly autonomous in accordance with the principle of subsidiarity. The interaction of the cells to form a network furtherly allows a secure and robust energy system. An infrastructure information system (IIS) supports the exchange of energy at a local and regional level by making information available. Examples for such information are flexibility potentials of the cells, different types of forecasts or technical aspects to control individual devices within the cells. New economic opportunities are provided for citizens by giving them the opportunity to participate in new business models ("sells"). Participation thus further increases the acceptance of the energy transition. The diverse stakeholder structure, which encompasses all stages of the cellular energy system's value-added chain, offered ideal conditions for the development and implementation of new cooperation models. C/sells shows how a smooth transition from demonstration to mass capability can look like.

Within the framework of C/sells, the Chair of Energy Economics has analyzed and evaluated existing market structures and new market design options for short-term electricity markets with a particular focus on balancing reserve markets. For this purpose, in a first step the balancing market segments were modeled by means of econometrics and machine learning. In a second step, trading opportunities for energy and flexibility on the existing and possible future markets were investigated in order to obtain optimal trading strategies, especially for balancing reserve markets.

Due to product definitions and the interferences with the electricity spot market (Day Ahead and Intraday), the balancing reserve markets offer various possibilities to sell flexibility of facilities or aggregated pools of facilities. The price and quantity uncertainties, e.g. caused by short-term changes in weather forecasts, are addressed with a stochastic optimization approach. The developed optimization model allows to derive optimal trading strategies with regard to both risk-neutral and risk-averse decision taking.

Supported by:

Federal Ministry for Economic Affairs and Energy

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)

Dogan Keles, Anthony Britto, Joris Dehler-Holland

Partners: KIT-IPD, KIT-IAI, KIT-ITI, KIT-ITEP, KIT-ZAR, KIT-AIFB, KIT-IPE, KIT-IISM, KIT-KSRI

Funding: Deutsche Forschungsgemeinschaft (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. This may be measurement data, metadata such as the extent of fatigue of batteries, or it may be other relevant data such as electricity rates.

Within the scope of this graduate college, Anthony Britto focuses on the economic puzzle of the energy-efficiency gap, which is the idea that the energy-conservation technology diffuses more slowly than its profitability would indicate. The focus of this research is a micro-economic modelling of different demand sectors in order to investigate the causes and possible solutions to this issue.

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Energy Systems Integration

Max Kleinebrahm, Armin Ardone

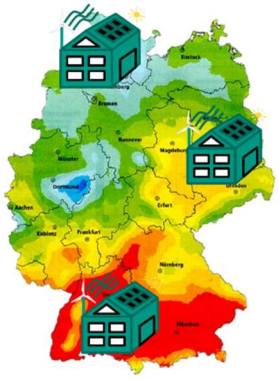
Partners: Forschungszentrum Jülich (FZJ), German Aerospace Centre (DLR), Max-Planck-Institute for Plasma Physics (IPP), Helmholtz-Zentrum Berlin (HZB), Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Helmholtz-Zentrum Potsdam German GeoResearchCentre (GFZ), Karlsruhe Institute of Technology (KIT)

Funding: Helmholtz Association

Duration: 2017 to 2021

The project "Energy Systems Integration" deals with those aspects of the energy system that make all individual components form a whole, i.e. all physical and IT-based interconnections as well as their structures and behaviors. It is incorporated in the broader challenge to coherently manage the resources energy, materials, and the natural environment. The cross-sectoral interaction between the various components of the energy system, such as producers, storage facilities, consumers and different transport systems, has not yet been sufficiently taken into account. For this reason, the focus is on the technological and economic interactions of energy system components. The aim of the research project is to design an environmentally sound, viable, flexible, stable and resource-efficient energy system by integrating and combining individual technologies and sectors.

Interactions within the energy system are represented by models, simulated for a variety of scenarios and verified by real data sets. The modelling from the component level to the process level up to the level of the energy systems leads to in-depth knowledge and applicable tools. For the development of robust scenarios, the trend towards individual and independent energy supply is analyzed. Therefore, the effects of self-sufficient residential buildings on the future energy system are examined in the Group "Decentralized energy systems and networks".



In addition to technologies already existing on the market (PV, batteries, biofueled heating systems, heat pumps), technologies under development, such as hydrogen storage systems are also taken into account. Initial studies have shown that 100% renewable energy-based electricity and heat supply is possible for single-family houses, taking into account technologies such as small wind turbines and long-term storage systems (Kleinebrahm et al.

2018). By considering different location factors such as country-specific regulatory conditions, weather conditions and comfort levels, big differences can be seen in the dimensioning of self-sufficient building energy systems. By combining different cluster approaches with optimization models, the economic gap between regular energy supply systems and self-sufficient renewable based energy supply systems is quantified for the European building stock.

ENSURE 2 – New Electrical Grid Structures for the energy transition

Manuel Ruppert, Christian Perau, Uwe Langenmayr, Christoph Fraunholz, Emil Kraft

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: 09/2019 to 08/2022

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?

At the IIP, in ENSURE 2 questions in the subprojects "Socio-economic analysis" and "Integrated system structures" are investigated. 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. Furthermore, generation and load time series with regionally and technically high-resolution for different scenarios in the electricity system of the future are simulated at the IIP. 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.

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FlexKälte – Flexibilisierung vorhandener Kälteanlagen und deren optimierter Einsatz in einer Realweltanwendung

Thomas Dengiz, Manuel Ruppert

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

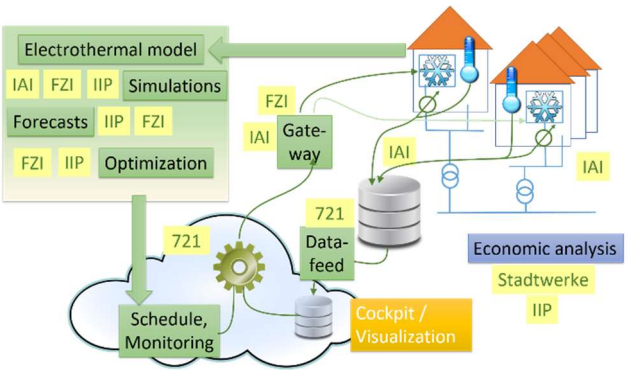
Funding: Federal Ministry for Economic Affairs and Energy

Duration: 01/2020 to 12/2022

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 figure shows an overview of the different tasks of the whole project.



The main tasks of our chair include:

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

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

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

Armin Ardone, Nico Lehmann, Daniel Sloot

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 Energy

Duration: 2019 to 2022

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 grid 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 (private individuals and market participants) 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 power generation systems, sector-coupling flexibility options (heat pumps, electric vehicles) and other flexible consumers are to be integrated. In order to ensure a reliable supply of flexibility, 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 grid 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 price/quantity combinations on the supply and demand side of flexibility are largely unknown and have to be assessed exemplarily before introducing a quota model. Instruments are developed, e.g. surveys, experiments and expert interviews, which allow the estimation of preferences of flexibility providers and thus the quantification of the socio-economic constraints. The aim is to achieve reliable and valid results and to include these results in the market simulations. In this way, market behavior can be observed and conclusions can be drawn on the market design.

Supported by:

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on the basis of a decision by the German Bundestag

MODEX-EnSAVes: Model Experiments - Development paths for new power applications and their effects on critical supply situations

Alexandra Märtz, Katrin Seddig, Florian Zimmermann, Christoph Fraunholz, Dogan Keles, Manuel Ruppert, Hasan Ümitcan Yilmaz

Partners: TU Dresden, Fraunhofer ISI, ESA², University of Duisburg-Essen, M-FIVE

Funding: Federal Ministry for Economic Affairs and Energy

Duration: 2019 to 2021

In the context of the energy turnaround, a completely new energy landscape is developing in Germany with increasing interconnection and the resulting interactions between the numerous actors and new technologies. Model-based energy system analyses are an important instrument for understanding these complex interrelationships and mechanisms of action. On this basis, specific impulses can be set which should drive system development in the desired direction. For this purpose, a wide variety of model approaches have been developed over the past decades, which now have a very broad methodological spectrum. In order

to investigate the function and effects of the different methods, to increase the transparency in system analysis and to promote the continuous improvement of the models, comparisons of model approaches should be pursued at regular intervals. Therefore, MODEX-EnSAVes is a methodologically oriented model comparison study, which is carried out on the basis of a specific use case.

The aim of the model comparison is to compare the results of different model approaches for the market rollout of new power applications and its effects on supply security. On the demand side, the model experiment focuses on the areas of e-mobility and heat pumps in residential buildings, for which the consortium applies various detailed models with a particular focus on the analysis. Since the investment decisions for passenger cars (i.e., modelled by TE3) and building heating systems are made by different actors, there are various influencing factors which are represented differently in the individual models. At the same time, the development dynamics in this area are crucial for the path towards an "All-Electric-Society", as is often proposed with regard to the implementation of climate protection goals. At the same time, increased electrification is also expected to have an impact on supply security, and the question arises in particular as to how critical supply situations such as situations with no wind in cold winter nights can be handled in the future. Therefore, the models for demand development are to be coupled with electricity market models (i.e., PowerACE). The latter should be used specifically for an analysis of future generation security, i.e., the adequacy of generation, backup capacities, demand side management, or reserve power plants for dealing with periods of high residual load. For this purpose, possible load curves for the new electricity applications will be derived from the demand models and used as input for the electricity market models. By iterating the models to be coupled, it will also be possible to reflect influencing factors such as the electricity price back to the demand models in order to consider mutual dependencies of the market launch with regard to e-mobility and heat pumps.

These are then used to investigate whether and how electricity demand can be met in the future by exploiting the flexibility potentials of the generation plants and demand applications. In particular, the focus will be on a year with extreme weather conditions. In this case, the weather year 2012 with comparably low temperatures at the beginning of February can be considered. By comparing the results of different electricity market models, it will be possible to determine in particular the impact of flexibility potentials on generation security.

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Modex-NET

Thomas Dengiz, Rafael Finck, Patrick Jochem, Armin Ardone, Katrin Seddig

Partners: Forschungszentrum Jülich, Deutsches Zentrum für Luft- und Raumfahrt, Forschungsstelle für Energiewirtschaft, Öko-Institut, RWTH Aachen University, Technische Universität Dortmund, Technische Universität Dresden

Funding: Bundesministerium für Wirtschaft und Energie (BMWi)

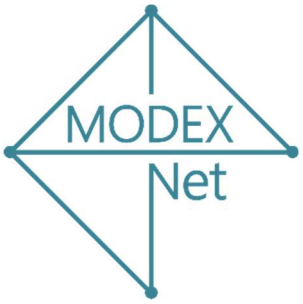
Duration: 2019 to 2021

Due to the increasing share of renewable energy sources in the European energy system, models of the transmission grid become more and more important for analyzing questions like the grid stability and the security of supply in future. To this end, many different transmission grid models exist. However, the used methodologies for modelling the transmission grid and the used input data for the model runs are quite diverse.

The goal of the project Modex-Net is to compare eight energy system models of the European transmission grid. The differences between the models are going to be identified and analyzed based on several case studies. The analysis comprises the methodological basics, the grid topologies and the used input data for the models. A special focus will be given to the used flexibilities for both the generation and the demand side. General recommendations for the adjustment and development of transmission grid models should be made based on the results of the analysis to foster the significance of transmission grid models for the energy transmission.

The following tasks were carried out in 2020:

- Harmonization of the input data of a historic year for all models
- Determination of the scenarios and the corresponding parameters
- Comparison of the market simulation results
- First runs of the grid models based on the input data from the market simulations
- A first analysis of the congestion management mechanisms of the different models
- Documentation and comparison of the different regionalization approaches for the demand and generation data



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OptTech - Analysis of the optimal and technology-specific storage mix for Germany and Europe in case of a complete conversion of the power supply to renewable energies by 2050

Hasan Ümitcan Yilmaz, Daniel Fett, Viktor Slednev, Joris Dehler-Holland, Dogan Keles

Funding: Stiftung Energieforschung Baden-Württemberg
Duration: 2019 to 2021

The OptTech project investigates how a secure power supply can be achieved through 100 % renewable energies (RE) by the year 2050 if fossil fuels are abandonded, and which storage technologies are required to compensate for fluctuations in the renewable energies. In particular, analyses what an economically reasonable composition of long-term and short-term storage technologies looks like for Germany and Europe until 2050 and to what extent both technologies complement or hinder each other in terms of capacity utilisation. This study examine the diffusion and optimal composition of different storage technologies under different energy policy scenarios.

First, the diffusion of decentralised PV battery storage systems based on microeconomic optimisation of households is predicted. Then the European energy system model PERSEUS-EU is further developed to model the long and short-term storage technologies. Using the diffusion scenarios of decentralised PV battery storage as input, the model will calculate the cost-minimal composition of renewable energies and central short-term and long-term storage technologies.

Profilregion Mobilitätssysteme Karlsruhe

Nora Baumgartner, Kira Schumacher, Manuel Ruppert, Alexandra Märtz, David Pflegler

Partners: FZI, Fraunhofer ICT, Fraunhofer IOSB, Fraunhofer ISI, Fraunhofer IWM, HsKA IEEM, HsKA IKKU, KIT ECON, KIT ETI, KIT FAST, KIT FAST, KIT IAM-WK, KIT IESL, KIT IFAB, KIT IFKM, KIT IfV, KIT IHE, KIT IIP, KIT IKFT, KIT IPEK, KIT IRS, KIT ITAS, KIT ITIV, KIT ITIV, KIT KASTEL, KIT KSRI, KIT MRT, WBK

Funding: Ministry of Science, Research and the Arts Baden-Württemberg (MWK)

Duration: Phase 1: 01/2016 to 12/2017; Phase 2: 03/2019 to 06/2021

Within the „Profilregion Mobilitätssysteme Karlsruhe", the research expertise and the development competence in the field of mobility systems available and located at Karlsruhe is combined and linked with industry. The project is funded by the federal state of Baden-Württemberg. Several institutes at KIT, Fraunhofer, Hochschule Karlsruhe and FZI (Forschungszentrum Informatik) are involved in the project and combine interdisciplinary research expertise.

Joint projects permit the partners to collaborate even closer, exploit synergy potentials and initiate a mutual and cross-institutional exchange of knowledge.

In Phase I IIP was part of the initialization projects „Transportation and Mobility in a changing society" and „Mobility in an urban environment – needs-oriented infrastructure solutions in future cities" with a focus on electric mobility topics.

In Phase II, IIP participates in the sub-project "Urban Mobility in Transition". Analyses focus on topics in the field of alternative drive trains and mobility concepts in the context of urban mobility solutions, related socio-economic implications as well as on analyses of potentials for electrifying Karlsruhe's taxi service.

As part of the Profilregion, the indicator system developed in the SuMo-Rhine project was applied to Karlsruhe Oststadt. Since the indicators are designed for the evaluation of municipalities, they were scaled to the district level and adapted. In the course of the application, the actual state of Karlsruhe Oststadt was evaluated and compared with possible scenarios. Mobility scenarios have been developed for this purpose. The assumptions were validated in expert discussions.

Baden-Württemberg

MINISTERIUM FÜR WIRTSCHAFT, ARBEIT UND WOHNUNGSBAU

PROFILREGION
MOBILITÄTSSYSTEME
KARLSRUHE

reFuels – rethinking fuels

Simon Glöser-Chahoud, Manuel Ruppert, Paul Heinzmann, Uwe Langenmayr, David Pflegler

Partners: Daimler, Audi, Porsche, MiRO, MWV, Ineratec, EnBW, Bosch, BorgWarner, Eberspächer, Freudenberg, L'Orange, Mahle, CAT, Kolbenschmidt, Mann+Hummel, weitere

Funding: Ministry of Transport Baden-Württemberg

Duration: 01/2019 to 12/2021

The utilization of renewable produced fuels (reFuels) is one of the main actions next to electric mobility on the way to CO_2 neutral mobility. These fuels use carbon-containing residues of agriculture and forestry, as well as, industry and municipality waste. Other fuel-generation processes compound CO_2 with hydrogen produced from the electrolysis process. All these fuels form the group of reFuels.

The project consortium comprises several institutes of the KIT and other partners from the industry. The aim of the project is to assess the complete value chain, from the production of the fuels to the application in the vehicle, of these fuels. The Institute for Industrial Production, on one hand, examines the impact of the production processes on the energy system of Baden-Württemberg and Germany. The focus of this task is the assessment of the additional flexibility of these processes, the CO_2 savings in the mobility sector and the increasing integration of renewable energy sources. On the other hand, a techno-economic analysis of the different production processes is conducted. This task aims to deliver deeper understanding of investment volumes and the cost structure of different process constellations. This includes aspects of logistics and necessary infrastructure, which have an additional impact on the final integration costs of the processes. Finally, the implementation of a pilot plant at the facility of one project partner will be simulated and assessed. The project results support deeper insights on reFuels, their production processes and useful applications. Furthermore, they help to further decrease the greenhouse gas emissions in the mobility sector.

RES-TMO - Concepts for an Integrated, Efficient and Sustainable Energy Supply and Storage in the Upper Rhine Region

Joris Dehler-Holland

Partners: University of Freiburg, TRION climate e.V., University of Strasbourg, University of Upper Alsace, badenova AG & Co. KG

Funding: European Regional Development Fund (ERDF) by the INTERREG V programme.

Duration: 01/2019 to 12/2021

The RES-TMO project develops regional concepts for an integrated, efficient and sustainable energy supply in the Upper Rhine region. The holistic nature of the concept is a particular focus. Due to the multidisciplinary approach of the project, different aspects of social acceptance, regulatory framework, economic feasibility and last but not least data security can be illuminated. The Chair of Energy Economics contributes its many years of experience in energy system analysis. In order to analyze scenarios for the development of the energy system, the Upper Rhine region was integrated as a separate

zone into the energy system model PERSEUS developed at DFIU/IIP. The basis for this is an extensive data research of energy data in the Upper Rhine region, such as the generation of electricity from renewable energy sources or existing transmission lines.

RES-TMO

The aim of the project work is the analysis of scenarios with high penetration of renewable energies in the Upper Rhine region as well as in the neighboring countries. Through the integration into the European system model PERSEUS, the exchange with neighboring countries can be taken into account as a non-negligible factor in a highly interconnected energy system. By this procedure cost-minimal scenarios are developed, which can incorporate supra-regional factors.

With increasing shares of renewables, storage technologies become relevant that can absorb "surplus" electricity and make it usable in times when little renewable energy is available. Therefore, storage technologies also play an important role in the evaluation of scenarios with high shares of renewable energies and are considered in the modeling.

Fonds européen de développement régional (FEDER)
Europäischer Fonds für regionale Entwicklung (EFRE)

interreg
Oberrhein
Rhin Supérieur

Helmholtz Portfolio Initiative "Safety and Security"

Hasan Ümitcan Yilmaz, Joris Dehler-Holland, David Pflegler

Partners: KIT-IKET, KIT-IPD

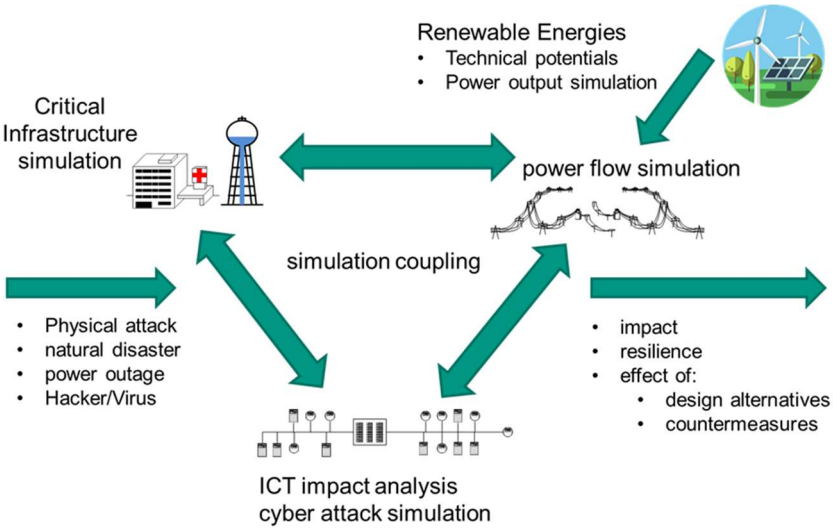
Funding: Helmholtz Association

Duration: started in 2013, ongoing

As part of the energy transition, power generation in Germany is changing from a centralised to a decentralised structure in which variable renewable energies dominate power generation. Among others, higher demand flexibility through intelligent load management as well as smart grid technologies at the distribution grid level shall help to cope with the increased complexity of the supply task. This will lead to an increasing diffusion of information and communication technologies (ICT) in the electricity sector in the future (e.g. via "smart meters"). The essential objective of the Helmholtz Portfolio Initiative "Safety and Security" is to develop future threat scenarios, which may arise in the context of the progressive networking, and to conduct model-based security assessments of critical infrastructures.

The focus is on the analysis of disruptions with possible cascade effects in electricity and communication networks as well as on the investigation of effects on other critical infrastructures such as health care and water supply.

HELMHOLTZ ASSOCIATION



Storage and Cross-linked Infrastructures (SCI) – for the Renewable Energy Age

Armin Ardone, Viktor Slednev, Thorben Sandmeier, Leandra Scharnhorst, Rafael Finck

Partners: Forschungszentrum Jülich (FZJ), German Aerospace Centre (DLR), Helmholtz-Zentrum Berlin für Materialien und Energie (HZB), Helmholtz-Zentrum Dresden-Rossendorf (HZDR), and Karlsruhe Institute of Technology (KIT)

Funding: Helmholtz Research Program (PoF III)

Duration: 2015 to 2020

The project focuses the challenges, which are attended by the German "Energiewende" in the field of energy storage systems and efficient infrastructures. The rising share of electricity generation from renewable energy sources requires three important new technical solutions:

- Adequate energy storage systems, which compensate the volatile generation and bridge seasonal fluctuations in supply and demand.
- Efficient infrastructures, which address the upcoming challenges of energy transmission and distribution.
- A cross-sector coupling (e.g. power-to-gas) to increase the energy systems' flexibility, efficiency and profitability and to secure reliable, flexible, efficient, and economic energy supply.

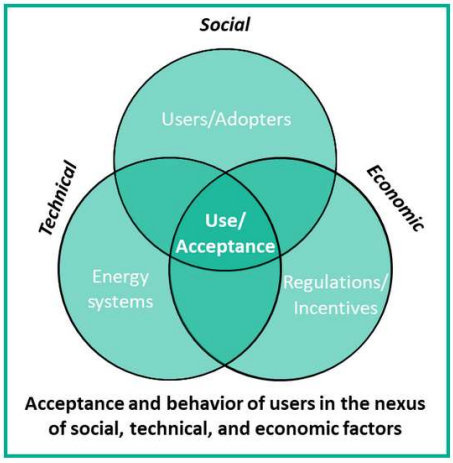
The whole project is divided into 6 thematic areas. The chair of Energy Economics is involved in Topic 6 Superconductivity, Networks & System Integration. One focus is the future development of the German transmission grid, in particular the interaction between the allocation of RES-E capacities and necessary transmission grid expansions. On this basis, the future of the German and its neighboring countries' power supply systems is analyzed under the assumption of a high share of renewable energies and the consideration of the transmission grid, storage system technologies and possibilities for sector coupling.

Furthermore, methods are developed to include the contribution of renewable energies, energy storage systems and flexible network elements in the context of system reliability. This includes the analysis of impacts of extreme weather events on the reliable network operation.

Another focus lies on the identification and usage of synergies between real world laboratories and energy system models. For this purpose the Energy Lab 2.0, a large-scale research infrastructure, has been established in the past years. At our chair we are working with 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.

This year, two tenants' lived in the Energy Smart Home Lab during a residential phase that took three months. The goal of this study was the analysis of the inhabitants' behavior, reactions and acceptance towards the provision of demand response induced by economic and non-economic incentives. As Figure 1 depicts this research topic emerges of the acceptance and behavior of users in the nexus of social, technical, and economic factors.



Acceptance and behavior of users in the nexus of social, technical, and economic factors

A mixed-methods approach was applied to assess the residents' behavior, including smart meter data, statistical analysis, surveys, interviews and the value scale. The incentives tested comprised economic incentives, as well as social and environmental incentives accounting for non-economic incentives.

During the residential period, the tenants' showed a high motivation and willingness to interact and participate, since they performed a high degree of flexibility regarding their demand response behavior. Hence, nearly all incentivized call to actions were performed, making social and environmental incentives as effective as economic ones.

Acceptance and behavior of users in the nexus of social, technical, and economic factors

Furthermore, the tenants adapted to their load shifting and peak shaving behavior to actively avoid power peaks even without incentives.

It is planned to realize further residential phases in order to gather comparative data, as well as refine the incentive system and undertake further research regarding security of supply.

SEES – Scientific Evaluation of Energy Services (Phase 2)

Sabrina Ried, Fritz Braeuer, Uwe Langenmayr, Alexandra Märtz, Hasan Ümitcan Yilmaz, Manuel Ruppert

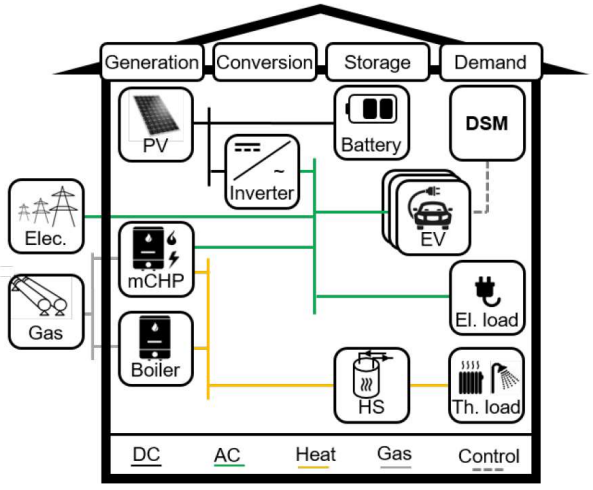
Partners: KIT-ENTECHNON

Funding: BMW Group

Duration: 2017 to 2020

BMW Energy Services develops innovative digital energy services for business and private customers. As part of a joint project, KIT has been researching various business models from a market perspective as well as from a techno-economic and ecological perspective. BMW Energy Services' products and services have been researched for different customer groups:

- BMW manufacturing plants
- Medium-sized companies
- Residential areas
- Private customers



Source: Braeuer et al 2019

This project was the second of two phases, where methodological principles were developed and applied. The aim of the second phase of the project was to conduct scientific research into various business models at BMW Energy Services. The business models address the planning and operation of local energy systems for the various customer groups, which in addition to energy consumers also include renewable energy systems, battery storage, and electric vehicles.

At the Institute for Industrial Production (IIP), four research groups worked on the evaluation of business models from the customer's point of view. For the evaluation, quantitative methods, data analytics, and model-based calculations based on economic efficiency and ecological sustainability were applied. Possible effects on the German electricity system from the large-scale application of the business models were also assessed, using the PERSEUS program package developed at the IIP. The project results regarding the German tenants electricity law and industrial battery storage systems were published and presented on conferences.

SuMo-Rhine - Sustainable mobility in the Upper Rhine region

Kira Schumacher, Katrin Seddig, Nora Baumgartner

Partners: Institute of Economics (KIT-ECON); Chair of Remote Sensing and Landscape Information Systems (University of Freiburg); Institute of Environmental Sciences (University of Koblenz-Landau), Image, City, Environment Laboratory (University of Strasbourg), Centre National de la Recherche Scientifique; University of Haute-Alsace; École Nationale Supérieure d'Architecture de Strasbourg; City of Lörrach

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

Duration: 2018 to 2021

The project "SuMo-Rhine - Sustainable mobility in the Upper Rhine region" is coordinated by the French-German Institute for Environmental Research (DFIU) of the Karlsruhe Institute of Technology (KIT). Eight other financed partners from Germany and France are represented in the project consortium. The European Union is supporting the project with a total of 1.36 million euros from the European Regional Development Fund (ERDF). The aim of the project is to comprehensively analyse and evaluate the cross-border transport systems existing on the Upper Rhine, using the conurbations of Strasbourg and Lörrach as examples. In the course of this, the project partners want to set up a novel "decision support system". Via a web application, the system makes measurable indicators for sustainable mobility accessible. Thus, cities, municipalities, mobility offices and mobility service providers should be able to identify potentials for improving the transport offer with low environmental impact and for increasing the market share of alternative modes of transport much more precisely than before.

During the half-time of the project, the project partners met for a two-day "retreat" in Hinterzarten in the Black Forest. The aim was to strengthen cooperation on a professional and a personal level. During the retreat, previously achieved results were reflected and synergies between the individual work packages were identified. In addition, the remaining project duration was planned in detail.

Furthermore, the project partners were able to organise participatory workshops. These were realised online because of the COVIR-19 pandemic. The DFIU took over the organisation in each case. Despite the difficult circumstances, the response was

great and the discussions with the participants were valuable and effective.

The first workshop took place in June 2020. In this context, the current state of the indicator system was presented. In the second part of the workshop, a range of indicators were discussed in small groups. The aim of this workshop was to cover the perspective of the local actors on the French side and to incorporate it into the further development of the indicator system. This workshop took place as a counterpart to the workshop organised in Freiburg in November 2019.

The second workshop, which was held in December 2020, served to present first results that could be achieved in interviews with municipal mobility and urban planners as well as with the analysis of policy documents. In addition, a round table was moderated in the second part of the workshop. The leading question was, whether COVID-19 represents an accelerator or an obstacle to sustainable mobility in urban areas.

Supported by:

Fonds européen de développement régional (FEDER)
Europäischer Fonds für regionale Entwicklung (EFRE)

interreg Oberrhein Rhin Supérieur

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

Alexandra Märtz, Manuel Ruppert

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

Funding: Federal Ministry for Economic Affairs and Energy

Duration: 07/2020 to 07/2023

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. To achieve this, it is crucial to focus on the available technologies, the players involved in the distribution grid and the further development of regulation simultaneously.

Based on the Smart-Meter-Gateway communication between energy industry actors and technical systems, possibilities of resilient design of information and payment flows shall be investigated with the aim to integrate decentralized and fluctuating generated electricity as efficiently as possible. In particular, the load flexibilities of electric vehicles will be taken into account. Today's markets and regulations will be further developed in key aspects and finally applied and evaluated on a pilot basis so that valid results can be derived for economic efficiency, security and acceptance of a market- and network-oriented provision of flexibility by households. For this purpose, models are developed to investigate mobility and charging behavior taking into account the temporal and spatial resolution as well as to identify distribution network areas with increased potentials of network congestion due to a high penetration of electric vehicles.

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Technical assistance to assess the potential of renewable liquid and gaseous transport fuels of non-biological origin (RFNBOs) as well as recycled carbon fuels (RCFs), to establish a methodology to determine the share of renewable energy from RFNBOs as well as to develop a framework on additionality in the transport sector[2]

Simon Glöser-Chahoud, Manuel Ruppert, Paul Heinzmann, Uwe Langenmayr, David Pflegler

Partners: Guidehouse, Fraunhofer ISI, ESA[2], TU Wien

Funding: European Union

Duration: July 2020 to July 2021

The general objective of the contract is to obtain detailed information on the potential of renewable fuels of non-biological origins (RFNBOs) and recycled carbon fuels (RCFs) in the EU from 2021 onwards; to provide producers of RFNBOs a framework enabling them to deliver evidence that the renewable electricity used in the production of their fuel is fully renewable; and to develop a general framework to measure the additionally of electricity in the EU transport sector.

The specific objectives of this contract are to assist the Commission in:

- Assess the potential of renewable liquid and gaseous transport fuels of non-biological origin as well as recycled carbon fuels, as defined in REDII, over the period 2020 to 2050 in the transport sector in the EU, including deployment potential, resource competition and decarbonisation potential (task 1).
- Develop detailed rules by which producers of renewable liquid and gaseous transport fuels of non-biological origin can provide evidence that they are using fully renewable electricity in the production of their fuel in order to establish the methodology under Article 27, paragraph 3, subparagraph 7 of REDII (task 2).

Develop a framework on additionality in the transport sector and develop different options with a view to determining the baseline of Member States and measuring additionally, in accordance with Article 27, paragraph 3, subparagraph 3 of REDII.

TrafoKommunE – Transformationsprozess für die kommunale Energiewende - sektorengekoppelte Infrastrukturen und Strategien zur Einbindung von lokalen Akteuren

Jann Michael Weinand, Max Kleinebrahm, 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 Energy (BMWi)

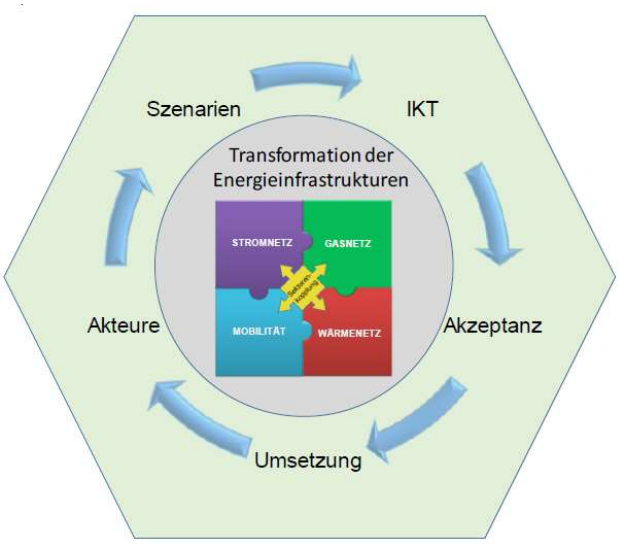
Duration: 2020 to 2023

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

[2] This project is hosted by the Chair of Business Administration, Production and Operations Management held by Prof. Schultmann.

(here 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. 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 on the one hand the analysis of the current building stock, together with 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 will be 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.



Holistic consideration of local energy supply

Supported by:

Federal Ministry for Economic Affairs and Energy

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

Armin Ardone, Rafael Finck, Viktor Slednev, Leandra Scharnhorst

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

Funding: Federal Ministry for Economic Affairs and Energy

Duration: 2019 to 2022

In system with large shares of renewable energies, weather events crucially impact power generation across the system. The project VERMEER aims at investigating the security of supply in Germany and central Europe during extreme weather situations. In a first step, extraordinary weather events are identified on the basis of historic weather reanalysis data. The main focus regards generation from solar PV and wind power generation. In a highly interconnected system, the possibility for cross-border exchange of electricity plays a key role to determine the security of supply. These cross-border capacities depend upon the thermal capacity of the power grid overhead lines, which are impacted by weather conditions such as wind speed and direction, which have a cooling effect or solar radiation, which has a heating effect. These interdependencies between weather and maximum

trading capacities are explicitly considered in the project. Expected results of the project are:

- Extensive evaluation of the characteristics of extreme weather events for long-term time scales, including spatial and cross energy carrier correlations.
- Calculation of highly spatially and technologically resolved infeed profiles.
- Determination of potential flexibility induced by cross border trade for the German electricity system under consideration of dynamic trading capacities for the coupled markets.
- Evaluation of the European internal market during extreme weather events including resulting deficits in generation (heat waves, calm periods, cold spells) and estimation of the remaining gap between supply and demand in Germany.

Supported by:

Federal Ministry for Economic Affairs and Energy

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

Christoph Fraunholz, Kim Miskiw, Malin Lange, Emil Kraft

Partners: TU Dresden, Fraunhofer ISI, ESA² GmbH

Funding: Federal Ministry for Economic Affairs and Energy

Duration: 07/2020 to 06/2023

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 CO_2 emissions to a sufficient extent, very 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 the current 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.

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Awards

- Dr. Dogan Keles has accepted the position of Professor at the Technical University of Denmark (DTU).

Completed PhD Dissertations and Habilitations

PhD dissertation: "Energy system analysis of energy autonomous municipalities"

Jann Michael Weinand

Attention on decentralised autonomous energy systems has increased exponentially in the past three decades, as demonstrated by the absolute number of real-world projects and the share of publications in the corpus of scientific literature. This is due to the energy transition and the related environmental awareness as well as the desire of citizens to play an active role in energy supply and to be less dependent on central markets and structures. However, local decision-makers, who often lack the necessary expertise, need decision support in energy system planning. To this end, this thesis follows the objective to develop novel methods for the technical, economic and environmental assessment of a large number of completely energy autonomous municipalities and their impacts on the overall energy system. Completely energy autonomous municipalities are disconnected from the gas and electricity grid and supply themselves with energy from plants owned and operated by the municipality.

Novel methods of energy system analysis were developed in this thesis as part of seven original research articles. Germany is used as a case study, but the general approach, methods and results are transferable to other contexts. First of all, the 11,131 German municipalities were clustered with regard to their suitability for decentralised energy systems. Based on this municipality typology, representative municipalities were selected to be investigated in an already existing holistic municipal energy system optimisation model (RE³ASON). This model was extended by novel and transferable approaches to design deep geothermal plants and district heating networks. These base-load capable technologies were selected to reduce the storage costs in energy autonomous municipalities. The technical feasibility and economic expenditures of energy autonomy could finally be determined in all 11,131 German municipalities by combining the extended energy system optimisation model with a stepwise linear regression.

The energy system optimisations showed that in the case of complete energy autonomy, deep geothermal plants in combination with district heating networks could reduce the total costs by up to 50%. On average, the energy system costs until 2030 in German municipalities increase by about 0.41 €/kWh in the energy autonomous case compared to the optimised reference case with grid connection. While a technical potential to achieve energy autonomy is present in 56% of the German municipalities, there seem to be no economic advantages through energy autonomy compared to the optimised reference energy system. The novel methodological approach of this thesis enabled to obtain optimisation results for a high number of energy systems (6,314 municipalities) with practicable computational expenses. In addition to the original data and planning tools published alongside the articles, the findings of this thesis can also support local decision makers in determining suitable municipal energy systems.
In order to increase the realizability of the case study results, some methodological extensions should be investigated in future studies such as other perspectives than that of a central planner, higher temporal model resolutions or social aspects like consumer acceptance of specific technologies or a security of supply below 100%.

PhD dissertation: "Fleets of electric vehicles in local energy systems with photovoltaic generation considering uncertainties"

Katrin Seddig

Electric vehicles (EV) are one promising technology towards a sustainable transport sector with reduced CO_2 emissions, especially when EVs are charged with electricity from renewable energy sources (RES). However, the fluctuating generation of RES as well as the driving patterns of the EV car users are subject to certain uncertainties.

In this thesis, a model is developed which can be used to identify the load shifting potential (LVP) of electric vehicle fleets considering the integration of photovoltaic (PV) generation and uncertainties. From this, approaches for the implementation of possible business models are identified, such as those that an EV aggregator could use to market the LVP resulting from the charging processes on electricity markets.

Different approaches using simulation, deterministic optimization, and stochastic optimization are developed to schedule the charging process of three different electric vehicle fleets (commuter, opportunity, and commercial) at a common charging infrastructure under uncertainty. In the setting of a car park case study, several technical constraints are considered when evaluating the LVP of the electric vehicle fleets to minimize charging costs and maximize the use of locally generated PV electricity. The two-stage stochastic mixed-integer optimization problem is solved by a Latin Hypercube-based sample average approximation method. Uncertainties of electricity generation by the PV system are considered by three different forecasting options and the mobility characteristics of the three electric vehicle fleets are modeled using a non-parametric probability density function (Kernel Density Estimation). In addition, a Monte Carlo simulation is applied to all approaches to represent the underlying stochastic profiles of PV generation, electricity prices, departure and arrival times, as well as the travel distances of the EVs before the charging process under consideration. By comparing the different chosen approaches with the deterministic optimum, the results of the methods can be compared.

The differences in charging costs and the use of locally generated PV electricity when applying the three approaches are identified and discussed. The numerical results illustrate the load shifting potential by different electric vehicle fleets in a car park with a common charging infrastructure according to different signals and taking thereby both technical constraints and uncertainties into consideration.

Habilitation: Analysis and Design of Electricity Markets[3]

Dr. Dogan Keles

The expansion of renewable energies in worldwide electricity markets is essential to reduce greenhouse gas emissions (GHGs) and to achieve the climate target of limiting the global temperature increase to well below 2.0 degree Celsius as decided in the Paris Agreement. Driven by this target, European electricity markets have already realized a large increase in the share of power production from renewable energy sources (RES). However, when it comes to providing flexibility to the system to balance the fluctuations of RES power production and to match supply and demand, policy makers and stakeholders still miss answers about the optimum combination of flexibility options. While flexible technologies, such as battery storages and Power-to-X technologies, and demand side management (DSM) are technically mature, their economics is still not. For this reason, decision makers seek advise with regard to regulations and market design adjustments that can increase the profitability of flexible technologies and allow their diffusion to the market.

Market design changes are not only required to enable emission-free technologies to enter the market, but also to ensure that sufficient flexible capacity remains in the market. This in turn is required to guarantee the so-called generation adequacy, which means that the available secured capacity in the market is able to meet electricity demand of consumers at all times. Since the liberalisation of the electricity markets, there has been an ongoing discussion among economists as to whether the energy-only-market (EOM) design is capable of achieving peak prices at sufficient frequencies and at sufficient levels to create incentives for new investments and to remunerate existing capacities in such a way that they can cover their fixed costs. Especially market frictions, such as regulatory price caps, can prevent equilibrium prices beyond the cap and lead to the missing-money problem.

In this context, the present book develops and applies models from Operations Research, Statistics and Machine Learning to analyse among others following research questions:

- What are the main driving factors of electricity prices and how can accurate price forecasting build on these factors?
- What price development can be expected under different market design options?
- Which design options for the electricity market can guarantee a sufficient level of investment and thus generation adequacy?
- What will be the effect of carbon emission reduction measures on prices and on the required capacity level to ensure generation adequacy?

The analyses on price drivers revealed that the total effect of renewable energies on electricity wholesale prices is indeed continuously growing, but a higher impact of coal and CO_2 prices can be detected when a specific time period is investigated. In particular, a high price effect can be observed in periods in which the input prices of electricity production showed high volatility or a strong decline. For instance, the impact of carbon and coal prices on German electricity prices was found to be twice as high as the impact of renewable expansion between 2011 and 2015. Beside these factors, also the developments in neighbouring electricity markets can have a significant impact on domestic electricity prices. The analysis of influencing factors of the Swiss electricity price has demonstrated the large effect of electricity demand in France and Italy and of German renewable power production on the Swiss market prices. This is due to the market coupling and large interconnection capacities between Central European countries that leads to price convergence through cross-border trading.

The price analysis also demonstrates that the vast expansion of RES power production with marginal cost of almost 0 EUR/MWh has put wholesale electricity price under pressure. Given the current level of prices, investments are hardly profitable. Besides, due to the fluctuating profile of RES power generation, it is expected that price volatility may increase in the next decade causing higher risk for revenues of power plants. This can additionally

[3] The habilitation colloquium was held on December 09, 2020. At the time of the publication of this report, the final submission of the thesis was pending.

hinder investments. Thus, discussions on market design changes have recently intensified and several design options including capacity remuneration mechanisms (CRMs) have been proposed to trigger investments and thus to guarantee generation adequacy.

The findings reveal also that CRMs can indeed ensure generation adequacy. Fluctuations of the overall electricity production capacity caused by investment cycles can be dampened by CRMs and extreme scarcity events can be prevented, since long-term capacity prices are likely to produce a more regular investment activity. However, the implementation of a CRM can lead also to market distortions, e.g. through cross-border effects. Even though cross-border impacts may be diverse according to different studies in the literature, there seems to be a consensus that a one-sided implementation of CRMs usually leads to negative spillover effects on a neighbouring market without a CRM.

Finally, a coordinated and ambitious policy is also required in other areas of decarbonisation. For instance, there is a high potential for power-to-X technologies to provide flexibility to the energy system and to support the integration of renewable energies. However, this potential cannot be deployed yet due to the price level in wholesale electricity markets and due to current end-consumer price tariffs. In this regard, policies like the exemption from fees and taxes or adapted grid usage fees for system beneficial behaviour are necessary to open the market for power-to-X installations in the residential and industrial sector and to exploit their flexibility potential.

Staff as of December 2020

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

Dr. Armin Ardone – Distributed Energy Systems and Networks

Dipl.-Math. Joris Dehler-Holland – Energy Policy

M.Sc. Christoph Fraunholz – Energy Markets and Energy System Analysis

M.Sc. Manuel Ruppert – Transport and Energy

Doctoral Researchers and their PhD-topics

Giacomo Benini*: Economic and environmental consequences of oil demand decrease due to electric vehicles market penetration.

Nora Baumgartner: Development of a modular system of intervention measures to increase the acceptance in the mobility context.

Anthony Britto: Theoretical underpinnings of technology diffusion and the energy-efficiency gap.

Joris Dehler-Holland: The policy driven diffusion of renewable energy technologies considering social dynamics.

Thomas Dengiz: Quantification and utilization of load flexibility potentials in German households focusing on Power-To-Heat.

Daniel Fett: Impacts of the increasing diffusion of PV-battery storage systems on the (central) electricity market.

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

Christoph Fraunholz: Market Design for the Transition to Renewable Electricity Systems.

Phuong Minh Khuong: Energy intensity in ASEAN countries: a retrospective decomposition analysis of the effects of urbanization and a model-based analysis of future developments.

Max Kleinebrahm: Analysis of renewable based energy supply systems for energy self-sufficient households.

Emil Kraft: Analysis and modelling of balancing power markets.

Uwe Langenmayr: Sector coupling electricity and mobility – Comparison of Power-to-Liquid, Power-to-Gas and Electric Mobility.

Nico Lehmann: Development and assessment of new market designs which enable bidirectional trading of flexibility on a cellular level.

Alexandra Märtz: A techno-economic analysis of impacts from electric vehicles on distribution grids.

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

Sabrina Ried: Sector coupling of electricity and mobility and implications on the curtailment of renewable energies.

Manuel Ruppert: Analysis of regional investment incentive schemes in congested electricity markets.

Thorben Sandmeier: Evaluation of flexible network elements in electrical transmission grids.

Leandra Scharnhorst: Demand response and security of supply in the residential and industrial energy demand sectors of tomorrow.

Maximilian Schücking*: Optimization model for commercial electric fleets considering uncertainties.

Viktor Slednev: Integrated generation and transmission planning modelling in large-scale power systems with a high RES share.

Daniel Sloot:** Peoples acceptance of and participation in energy systems, specifically consumer participation in demand response programs.

Zongfei Wang*: Uncertainties in energy demand of future private households (with a focus on stationary storages, electric vehicles and photovoltaic systems).

Jann Michael Weinand: Municipal energy autonomy: a model-based analysis of the technical, economic and environmental impacts from a micro- and a macroeconomic perspective.

Christian Will*: CO_2-neutral charging of electric vehicles: a techno-economic analysis from OEM-perspective.

Hasan Ümitcan Yilmaz: Analyzing decarbonization strategies for Europe with advanced energy system modelling.

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

*external researchers

**Post-doctoral researcher

International Collaboration

Location: Reading, United Kingdom

Who: Max Kleinebrahm

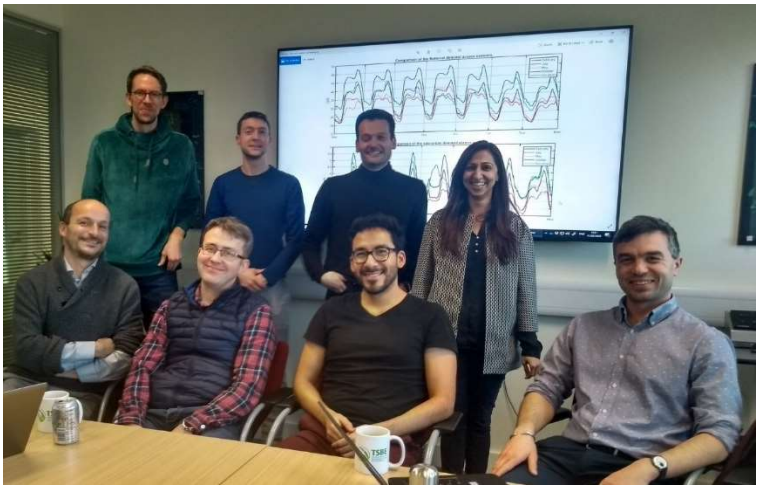
Host: Prof. Jacopo Torriti, University of Reading, School of the Built Environment

Period: January to March 2020

Short description of stay: From January 10th 2020 till March 27th 2020, CREDS (Centre for Research into Energy Demand Solutions in UK) enabled Max Kleinebrahm to undertake a research stay at the University of Reading in Professor Jacopo Torriti's research group which is working on topics related to flexibility in energy demand. He was integrated into the team and was given numerous opportunities to present his work on residential behaviour modelling, with the aim of better understanding the energy demand in the building sector. In many interesting discussions they were able to gain new perspectives on the research topic and thus were able to develop novel approaches for residential energy demand modelling based on machine learning algorithms. One of the highlights of his research stay was the visit of the CREDS Core Team at Oxford University, where he presented their research activities to the CREDS Consortium in a "Brown Bag" seminar and in a webinar in order to reach as many CREDS members as possible.

Publication:

Using neural networks to model long-term dependencies in occupancy behavior. Kleinebrahm, M.; Torriti, J.; McKenna, R.; Ardone, A.; Fichtner, W. 2020. Karlsruher Institut für Technologie (KIT). doi:10.5445/IR/1000126271



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
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 are introduced as well as associated technologies. 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 ~100 students

PD Dr. rer. pol. P. Jochem
Prof. Dr. R. McKenna

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 ~40 students

Apl. Prof. Dr. rer. pol. M. Wietschel
Dipl.-Math. J. Dehler-Holland

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 ~30 students

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

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 Trade and Risk Management ~150 students

Prof. Dr. rer. pol. D. Keles
M. Sc. E. Kraft

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 ~15 students

Dr. rer. nat. P. Plötz
M. Sc. T. Dengiz
Dipl.-Inf. 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 ~15 students

Prof. Dr. rer. pol. W. Fichtner

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 ~20 students

Dr. rer. pol. A. Ardone
Prof. Dr. rer. pol. D. Keles
M. Sc. T. Dengiz
Dipl.-Inf. 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 ~20 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 ~65 students
Apl. Prof. Dr. rer. nat. U. Karl
M.Sc. U. Langenmayr
Dr. J. M. Weinand

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 ~200 students
Prof. Dr. rer. pol. W. Fichtner
M. Sc. M. Kleinebrahm

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 Trade 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)

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Elektromobile Flotten im lokalen Energiesystem mit Photovoltaikeinspeisung unter Berücksichtigung von Unsicherheiten. PhD dissertation. Seddig, K. 2020, May 19. Karlsruher Institut für Technologie (KIT). doi:10.5445/IR/1000119329

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