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Reichelt, David Georg; Kühne, Stefan; Scheller, Fabian; Abitz, Daniel; Johanning, Simon

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Towards an Infrastructure for Energy Model Computation and Linkage

David Georg Reichelt[1] Stefan Kühne[2] Fabian Scheller[3] Daniel Abitz[4] Simon Johanning[5]

Abstract: Decision makers strive for optimal ways of production and usage of energy. To adjust their behavior to the future situation of markets and technology, the execution of different models predicting e.g. energy consumption, energy production, prices and consumer behavior is necessary. This execution is itself time-consuming and requires input data management. Furthermore, since different models cover different aspects of the energy domain, they need to be linked. To speed up the linkage and reduce manual errors, these linkage needs to be automated. We present *IRPsim*, an infrastructure for computation of different models and their linkage. The *IRPsim*-infrastructure enables management of model data in a structured database, parallelized model execution and automatic model linkage. Thereby, *IRPsim* allows researchers and practitioners to use energy system models for strategic business model analysis.

1 Introduction

Prediction of future developments is a key value for acting successfully in markets. This prediction is often done by models, which mirror the reality using simplified assumptions about the real world. This is particularly relevant in the energy domain, since the transition of power production from conventional power plants to renewable power plants changes market behaviors [Fa16]. Therefore, municipal energy utilities need to rearrange their portfolio. These portfolios need to be adjusted based on the adoption behavior of customers. To support decision makers of municipal energy utilities, *IRPopt* [Sc18] models the economic effects of changed portfolios and *IRPact* allows insights in the adoption behavior of the customers.

The manual execution of these models suffers from three problems: (1) Their input data, including parameters of different commercial actors such as customers or producers, engineering components such as markets or loads and component relations such as energy flow edges, are complex to handle. (2) The execution of models is too resource-intensive to be executed on a desktop PC on a regular basis. (3) While single models cover their

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[1] Universität Leipzig, Universitätsrechenzentrum, Abteilung Forschung und Entwicklung, dg.reichelt@uni-leipzig.de

[2] Universität Leipzig, Universitätsrechenzentrum, Abteilung Forschung und Entwicklung, kuehne@uni-leipzig.de

[3] Technical University of Denmark (DTU), Department of Technology, Management and Economics, Energy Systems Analysis, fjosc@dtu.dk

[4] Universität Leipzig, Institut für Schwarmintelligenz und Komplexe Systeme, abitz@informatik.uni-leipzig.de

[5] Universität Leipzig, Institut für Infrastruktur & Ressourcenmanagement, johanning@wifa.uni-leipzig.de

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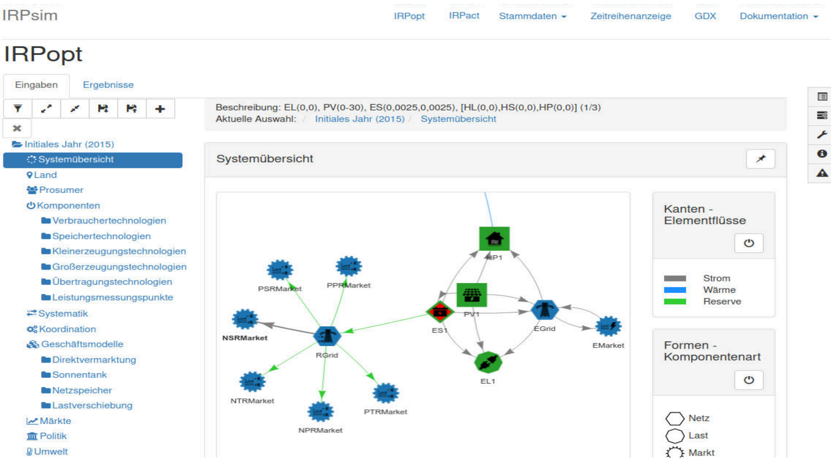
respective perspective on the domain, their linkage enables a broader view while preserving the advantage of each model [We96]. Manual organizing the linkage of models is time-consuming and error-prone.

To overcome these problems, we present *IRPsim*, a software framework capable of (1) managing input and output data for energy system models, (2) executing different energy system models and (3) linking different models. The implementation of *IRPsim* aims for usability by domain experts without modeling knowledge. In this paper, we describe the architecture of *IRPsim*. The basic *IRPsim*-infrastructure and the *IRPopt*-model, which can be plugged into *IRPsim*, are developed and in use [Kü19; Sc18; Sc20]. Currently, the *IRPact*-model and the model linkage are in an advanced development state. A screenshot of the graphical user interface is depicted in Figure 1.



Beschreibung: EL(0,0), PV(0-30), ES(0,0025,0,0025), [HL(0,0),HS(0,0),HP(0,0)] (1/3)
Aktuelle Auswahl: Initiales Jahr (2015) / Systemübersicht

Fig. 1: Graphical User Interface of IRPsim

The remainder of this paper is organized as follows: At first, we describe models suitable for execution in *IRPsim* (Section 2). Based on the models, we describe the architecture of *IRPsim* itself (Section 3). Afterwards, an overview over related work is given (Section 4). Finally, we summarize our work and give an outlook to future work (Section 5).

2 Techno-socio-economic Perspective on Municipal Energy Systems

Decision makers in the energy domain are confronted with making informed decisions within the scope of continuously evolving systems. With the help of techno-economic optimization models, e.g. deeco [Br97], DER-CAM [St14], EnergyHub [Ge07], XEONA [MWB05] or *IRPopt* [Sc18], decision makers of municipal utilities can investigate the performance of an energy system under different circumstances from different market actors perspectives. In subsection 2.1, we give an overview about the optimization model *IRPopt*. While techno-economic modeling can capture technological interactions, it cannot cover commercial processes that arise between multiple market participants. These can be modeled by an agent models called *IRPact*, which is described in subsection 2.2. To evaluate new business models by providing insights into the operational performance of the energy supply system and the interactions between the adoption decision of market actors, we propose a combined analysis of the techno-economic and socio-economic dynamics. This combination is described in subsection 2.3.

2.1 The Techno-economic Optimization Framework *IRPopt*

The techno-economic optimization framework *IRPopt* (Integrated Resource Planning and Optimization) [Sc18] supports decision makers of municipal energy utilities regarding future portfolio management. The mathematical optimization model allows for a policy-oriented, technology-based and actor-related assessment of varying energy system conditions in general, and innovative business models in particular. The integrated multi-modal approach is based on a novel six-layer modeling framework built on existing high-resolution modeling building blocks.

The optimization model, which has been implemented in GAMS/CPLEX (General Algebraic Modeling System[6]), allows for solving mixed-integer problems in a (quarter-)hourly resolution for perennial periods. The major objective is to maximize profits from different actor perspectives. Thereby, *IRPopt* provides a novel actor-oriented multi-level optimization framework. This is achieved by explicitly modeling municipal market actors on one layer and state-of-the-art technology processes on another layer. Resource flow interrelations and service agreements mechanism are modeled on and between the different layers. Individual participating market actors and the spatially distributed load, storage and generation technologies are modeled separately. Furthermore, multi-party cooperation is incorporated. Individual actors hold bilateral contracts with each other that handle the business transactions.

Due to the chosen approach, decision making of different modeled market actors is unbounded rational [WB09]. In addition to models covering local utilities and large independent energy producers as fully rational actors [WB09], *IRPopt* permits to determine the optimal operation dispatch and thus the optimal profitability index from different market actor perspectives. Thereby, the effects of decentralized business models, such as self consumption, regional self marketing and neighborhood energy storage systems can be modeled [Sc17].

2.2 The Socio-economic Agent-based Model *IRPact*

While techno-economic modeling can capture technological interactions, it cannot endogenize the commercial processes that arise between multiple market participants. Structural

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[6] https://www.gams.com/

decisions of different market actors are often related to bounded rationality and thus are not fully rational. The adoption of technology innovation does not just depend on the qualities of the innovation. Instead, it takes place within a complex social system, in which the diffusion of the respective innovations depends on many factors and mechanisms [Sc07]. Innovations need to encompass the dynamics of the market setting by including the mental decision structures, such as personal characteristics and behavioral attitudes, as well as conscious and subconscious purchase decisions of stakeholders in general and of customers in particular.

For the representation of such socio-economic processes the approach of empirically grounded agent-based modeling turned out to be one of the most promising approaches as it allows for considering various influences on the adoption process on a micro-level [ZV19]. Additionally, a large share of available applied research already deals with environmental and energy-related innovations [SJB19].

Socio-economic modeling does not only account for the heterogeneity of bounded-rational mental behavior patterns, which are not only based on economic thinking, but also considers the social structures of market actors [Bo02]. This approach makes it possible to simulate acceptance and diffusion of innovations by various customer types and utilities considering different decision-making and network models, as well as the temporal and regional differences in the diffusion process.

The agent framework *IRPact* (Integrated Resource Planning and Interaction) allows the simulation of the mentioned diffusion processes. *IRPact* is implemented in Java using Jadex [BP12][7]. The Jadex framework allows the implementation of agents, based on the Belief-Desire-Intention model of Bratman [Br87], which is grounded on folk-psychology and permits the simulation of human reasoning and irrational decisions making. Therefore, this model is used in a wide range of social simulations [AG16] and diffusion processes in social networks [BCP18].

2.3 Integration of *IRPopt* and *IRPact* in *IRPsim*

Model	Domain	Input	Output	Time Scale	Language
IRPopt	Energy Dispatch Modeling	Techno-economic Parameters	Profitability Indices	≥ 15 mins	GAMS
IRPact	Techn. Diffusion Modeling	Socio-economic Parameters	Adoption Rates	Monthly	Java

Tab. 1: Summary of Model Properties

The properties of *IRPopt* and *IRPact* are summarized in Table 1. The adoption rate of individual market actors regarding energy-related business models directly affects energy supply networks and process technologies. In contrast, the optimized operation dispatch (profitability index) of individual actors in terms of a given supply network can be considered

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[7] Official website: `https://www.activecomponents.org/`

a single influencing aspect of the decision behavior of other market participants. In general, socio-economic behavior patterns of market actors have system impacts on the techno-economic business performance of the energy supply system and vice versa. Such feedback effects between decisions of market actors and the performance of a certain energy supply network can be simulated by a combination of a bounded rationality model with an unbounded rationality model as initially described by [WB07].

The multi-model *IRPsim* (Integrated Resource Planning and Simulation) [SJB18] represents such a combined approach by integrating the bounded and unbounded rationality modeling approaches *IRPact* and *IRPopt*. While the model *IRPact* (Integrated Resource Planning and Interaction) calculates the adoption rates of individual market actors, the model *IRPopt* (Integrated Resource Planning and Optimization) optimizes their profitability indices. The mutual dependencies of the coupled models result in an interactive and dynamic energy model application for multi-year business portfolio assessment.

The integration of both modeling approaches is realized by a common data basis and by linking input and output parameters. Both models consider the same market participants, but from different perspectives. While in *IRPopt*, for example, contractual relationships and optimization authorities of actors are parameterized, the underlying mental models and social relationships are relevant for *IRPact*. Where optimization results of *IRPopt* of a certain system infrastructure provide costs and revenues for each of the participating actors in terms of operational management, the simulation results of a certain social system in *IRPact* shows the adoption rate for each of the participating actor. This, in turn, affects the system infrastructure and changes the parametrization of *IRPopt*. At the same time, the reevaluated profitability of the adoption decision influences the decision making of the participating actors and thus the adoption process of *IRPact*.

3 Technical Architecture of the Simulation Platform *IRPsim*

The application of the *IRPsim* models *IRPopt* and *IRPact* implies a number of technical and non-functional requirements. The practical application within industrial usage scenarios requires systematic management of input and output data, handling of execution resources and organization of model linkage. These aspects require support by a software infrastructure. The workflow is depicted in Figure 2.

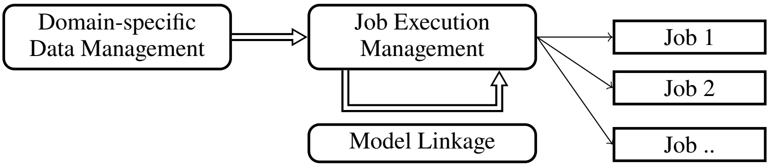

Fig. 2: Requirements Overview

In [Kü19] we describe how the essential aspects usability, adaptivity and flexibility are realized in the *IRPsim*-infrastructure based on master data management, scenario-based configuration and a model-driven development. In the following we concentrate on aspects aiming at the integration of *IRPopt* and *IRPact*.

IRPopt and *IRPact* process hundreds of input and output parameters – scalars, arrays, sets and time series. The management and assignment of input and output data is described in subsection 3.1. Based on the input data and model specifications, the execution is managed, which is described in subsection 3.2. To ease the use of different models and their interaction, model linkage is handled, which is described in subsection 3.3.

3.1 Data Management

Input and output data collection of both models is done by researchers. They gather concrete input data from various sources, e.g. stock exchange publications, weather forecast databases and scientific literature. The future of the energy world may be shaped by different scenarios, as e.g. business may be continued as usual or the political incentives for the energy transition might be increased heavily. During the temporal scope of the model, these scenarios change, therefore the forecast scenarios of 2015 are not the same as the scenarios of 2020. Furthermore, some input parameters are functions of other parameters, e.g. the tariff for 1 kWh of a private household in year n might be the tariff of year $n-1$ plus 5%.

The *IRPsim*-infrastructure supports researchers by storage, checks for completeness and checks for correctness of data. This is done using the data model depicted in Figure 3. All input and output data are `DataSets`, i.e. instances of data defined by year and scenario. Most of them consist of `StaticData`, i.e. a concrete value or a concrete time series with values in different resolutions, e.g. quarter-hourly, hourly or weekly.

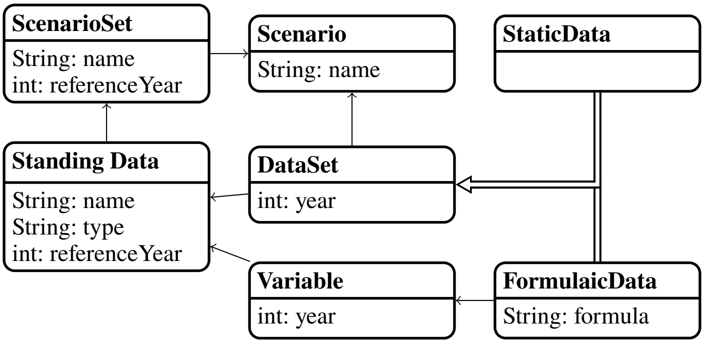

Fig. 3: Input Data Model

To assign input `DataSets` to input parameter of models, the model input parameters are enhanced by annotations which specify unit and name of each parameter. For the concrete assignment of `DataSet`-instances, they contain references to a `StandingData`-instance which contains the *IRPsim*-DSL name as `type` (e.g. *par_F_E_EGrid_energy*, an energy tariff), a human readable name (e.g. *power tariff spot market*) and a reference year, e.g. 2020. For each `StandingData` instance, for every scenario and every concrete year, a `DataSet` instance may be present. Besides being `StaticData`, a `DataSet` might be `FormulaicData`, which contains formulas referencing `Variables`, which also are `StandingData`, e.g. the tariff might be 5% more then the data contained in the `StandingData`-instance of the last year. This data model is generic for every energy model currently used, since they all require input data in the form of time series or scalar values with the same metadata.

3.2 Execution of *IRPsim* models

The model execution consists of the parametrization with values from the common data basis and the subsequent model call. Both will be described in this subsection.

Parametrization To execute the *IRPsim* models, the input parameters need to be transformed to a format readable by the underlying execution environment. The transformation process includes the formatting of the content, e.g. to roll out a time series to a given resolution, and the technical formatting, e.g. creating a GDX database for the GAMS environment or creating a JSON file for an agent-based model in Java.

This parametrization process uses a model experiment specification as input, which is created by the user using a web frontend. The model experiment specification contains mappings from parameters and its dependencies to DataSets or manually configured data. The *IRPsim* infrastructure contains generic code which reads model experiment specifications from the frontend, queries the database for the concrete data and performs the roll out of time series. Afterwards, for every model type, the parametrization needs to be implemented separately.

Model Call Model calls are initiated as independent Java sub-processes. In the case of *IRPopt*, which is represented as a GAMS model, the associated API of the GAMS environment is used. *IRPact* is executed as a JAR, which manages its own call.

Since model call jobs are long-running and input data or models itself may contain bugs, the view of intermediary results might speed up the modeling and bug fixing efforts. Therefore, models may write intermediary results to CSV files which are continuously read by the system and imported into the database. Thereby, the user may view intermediary results and spot anomalies or unexpected behavior during the call.

Currently, the parallelization of model call jobs are limited to single-server systems. To keep the called environment stable and efficient, a maximum amount of parallel running jobs must be specified. As a rule of thumb, we usually allow one job for two CPUs and 2 GB of RAM. Since model calls are time-consuming and resource-intensive, and the capacities of single-server machines are limited, we plan to expand the possibilities for parallelization of the *IRPsim* infrastructure to cluster environments. The distribution of model calls will be realized by the job scheduling system Slurm.

3.3 Model Linkage

IRPopt and *IRPact* represent the techno-economic and socio-economic perspective on future developments of municipals energy supply systems. They are parameterized based on the same data basis. The feedback loops between both perspectives, i.e. the impacts of the techno-economic model to the socio-economic model and vice versa are handled as functional dependencies between the two models.

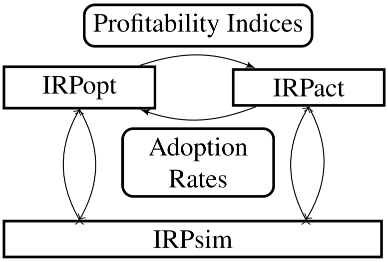

Fig. 4: Interaction of Different Models

In Figure 4 this approach is visualized based on the example of profitability indices and adoption rates as discussed in section 2: *IRPopt* predicts business-specific values, like profitability indices, and needs data of technology adoption rates. *IRPact* requires business-specific values, like profitability indices, and produces technology adoption rates. To support these inter-model dependencies, combined model execution provision was implemented. In these combined executions, the user selects a combined execution mode specifying which models to combine. Afterwards, they define which years are executed. The remaining years are interpolated. When the definition of parameters is finished, the model can be started.

Parameter Exchange Output parameters are by convention prefixed by `par_out`, e.g. `par_out_PowerMeasurement`. To exchange parameters between models, the input-parameters of one model are parsed and matched with the output parameters of another model. If their names match, e.g. if *IRPact* has an input parameter `par_PowerMeasurement` and *IRPopt* has an output parameter `par_out_PowerMeasurement`, the output values of the preceding year are transformed to an input parameter of the current year.

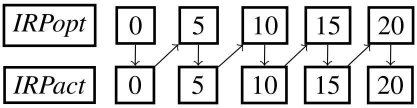

Fig. 5: Execution Dependencies

Execution Dependencies Since parameters are exchanged, the years can only be executed sequentially, i.e. since year 0 of *IRPact* relies on the profitability indices of year 0 of *IRPopt*, it needs to wait until *IRPopt* is finished, and since year 5 of *IRPopt* relies on the adoption rates of year 0 of *IRPact*, it needs to wait until *IRPact* is finished. Therefore, a parallelization of one computation is not possible. However, different scenarios may be computed in parallel.

4 Related Work

A combination of techno-economic and socio-economic modeling perspectives is necessary to provide comprehensive support to decision makers of municipal energy systems. The approach to look at different levels of abstraction, views or sectors of energy systems by means of specialized models and to combine them to answer complex questions is discussed in existing literature. Advantages include easier application, greater flexibility and better maintainability of the specialized models [KKS20; MS00].

The combination of different models can be achieved by different approaches. Wene [We96] distinguishes between soft-linking (informal linking) and hard-linking (formal linking). With soft-linking, the processing and transmission of the information transferred between models is carried out externally, for example by the model user. The output of one model is used as input for the other. With hard linking, the degree of integration between the models is higher. The transfer of information is an essential part of the modeling itself. Böhringer and Rutherford [BR08] distinguish three categories of integration. Linking of independently developed models, coupling of models by choosing one of the models as the main one and complementing it with a representation of the other in a reduced form, and completely integrated models based on developments of solution algorithms for mixed complementarity problems. Soft-linking is typical for combining energy-sector specific and other models [KKS20].

In *IRPsim* we follow the soft-linking approach. The exchange between *IRPopt* and *IRPact* is realized by mutual parameter transfer, which happens at defined synchronization points (annual slices). By using the common simulation platform IPRsim further synergy effects are created: we use a common database for the parameterization of the models, scenario-based configuration, parallelization of execution processes and merge simulation results synchronously during execution and afterwards.

5 Summary and Outlook

We presented *IRPsim*, an infrastructure for energy model computation. *IRPsim* enables the input and output data management, the configuration of model executions, the linkage of models and the creation of output graphs. This is done using an input database, relying on MariaDB, a parametrization component, rolling out the data and producing GDX and JSON, an execution component automating the call of GAMS and Java models and an output database, managing CSV and GDX result data. Our approach is summarized in Figure 6. Thereby, *IRPsim* supports researchers and practitioners in predicting the effects of the energy transition and enables practitioners to react accordingly in their particular markets.

In the future, *IRPsim* might be extended in the following ways: (1) *Model Support Extension*: Currently, *IRPsim* supports *IRPopt* and *IRPact* and their data exchange. We plan to extend *IRPsim* to be usable for more models, e.g. a balancing energy model, a spot market price model or a political economy model. (2) *Analysis Capability Extension*: Currently, *IRPsim* allows for the creation of graphs to create insights into the model behavior. We plan to further extend the amount of available graphs. (3) *Duration Prediction*: The same model has different performance with different input data, e.g. *IRPopt* increases its computation time when more customer groups are defined. To enable reasonable model execution job

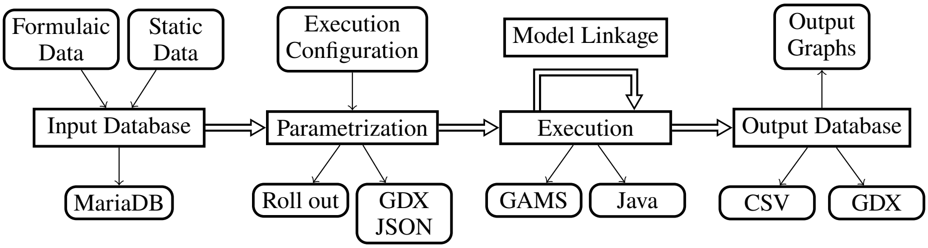

Fig. 6: Architecture Overview

prioritization, we plan to implement a duration prediction based on input data. Thereby, *IRPsim* will be even more efficient enabling research of effects of the energy transition.

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