Project Report L18/1: Modelling toolbox IRPopt – current state and use cases

09/2022

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Topic: LC-SC3-SCC-1-2018-2019-2020: Smart Cities and Communities

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About SPARCS

Sustainable energy Positive & zero cARbon CommunitieS demonstrates and validates technically and socioeconomically viable and replicable, innovative solutions for rolling out smart, integrated positive energy systems for the transition to a citizen centred zero carbon & resource efficient economy. SPARCS facilitates the participation of buildings to the energy market enabling new services and a virtual power plant concept, creating VirtualPositiveEnergy communities as energy democratic playground (positive energy districts can exchange energy with energy entities located outside the district). Seven cities will demonstrate 100+ actions turning buildings, blocks, and districts into energy prosumers. Impacts span economic growth, improved quality of life, and environmental benefits towards the EC policy framework for climate and energy, the SET plan and UN Sustainable Development goals. SPARCS co-creation brings together citizens, companies, research organizations, city planning and decision making entities, transforming cities to carbon-free inclusive communities. Lighthouse cities Espoo (FI) and Leipzig (DE) implement large demonstrations. Fellow cities Reykjavik (IS), Maia (PT), Lviv (UA), Kifissia (EL) and Kladno (CZ) prepare replication with hands-on feasibility studies. SPARCS identifies bankable actions to accelerate market uptake, pioneers innovative, exploitable governance and business models boosting the transformation processes, joint procurement procedures and citizen engaging mechanisms in an overarching city planning instrument toward the bold City Vision 2050. SPARCS engages 30 partners from 8 EU Member States (FI, DE, PT, CY, EL, BE, CZ, IT) and 2 non-EU countries (UA, IS), representing key stakeholders within the value chain of urban challenges and smart, sustainable cities bringing together three distinct but also overlapping knowledge areas: (i) City Energy Systems, (ii) ICT and Interoperability, (iii) Business Innovation and Market Knowledge.

Partners

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Dissemination level

PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	

Deliverable administration

No & name	**Annex to D4.3** **Report on the implemented demonstrations of solutions for energy positive blocks in Leipzig**				
Status	Draft	**Due**	M36	**Date**	2022-09-30
Author(s)	Philipp Lerch[1], Karl Specht[1], Hendrik Kondziella[1], Thomas Bruckner[1]				
Description of the related task and the deliverable. Extract from DoA	**L18-1:** Further developing and refining the resource planning and optimisation (IRPopt) modelling approach and of the web-based software environment to allow long-term and short-term scenario calculations. This includes the integration of cascading time slices, policy goals such as renewable energy quota or CO2 emissions and standard reporting tools.				
Participants	ULEI				
Comments	-				

V	Date	Authors	Description
0.1	30/09/2022	Lerch	First draft
0.2	05/10/2022	Lerch	Structural improvements
0.3	30/01/2023	Lerch	Additional references added

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1. IRPOPT INTRODUCTION

Brief description

The IRPopt (Integrated Resource Planning and optimization) modelling framework, primarily developed by Scheller (Fabian Scheller, 2018) at the Institute for Infrastructure and Resources Management at the University of Leipzig, is a mixed-integer linear programming modelling framework for economic dispatch with profit maximization as the primary objective. IRPopt is implemented on the modelling infrastructure platform IRPsim (Reichelt, Kühne, Scheller, Abitz, & Johanning, 2021) and both are open source licensed under GPLv3 (Fabian; Scheller & Reichelt, 2022). IRPopt is a dynamic, deterministic, and discrete municipal energy system model with adjustable temporal granularity and rolling optimization horizon. Its mathematical model is written in GAMS and it uses the IBM CPLEX solver.

With this framework, energy system models can be built out of a large portfolio of consumer-, storage-, producer- and distribution technology components and energy carriers like electricity, heat, hydrogen and multiple fossil fuels. Besides the energy flow between components, the monetary flow between agents like different suppliers, distributors, consumers or regulators can be modelled. The objective function maximizes profit. One major constraint is that demand (e.g., electricity) must be covered in each time step if no consumer side load shifting is allowed. With consumer side load shifting allowed, demand must be covered over adjustable temporal load shifting periods. Load shifting settings allow to shift 0 – 100% of load within the specified load shifting period and are adjustable.

IRPopt was already applied in the past to answer a wider range of research questions, for example, the potential of residential demand response through variable electricity tariffs (Fabian Scheller, Krone, Kühne, & Bruckner, 2018) or competition between simultaneous demand-side flexibility options in the case of community electricity storage systems (Fabian Scheller, Burkhardt, Schwarzeit, McKenna, & Bruckner, 2020), see also the following chapter with IRPopt use cases. The main advantages of IRPopt compared to many other models are modularity, temporal granularity and rolling optimization horizon. The modularity allows to build models efficiently out of a large portfolio of technology components over whole value chains. The temporal granularity can be freely adjusted, for example to ¼ hourly resolution. The optimization horizon of one year including an adjustable rolling horizon covers seasonal effects while keeping perfect foresight restricted. A more detailed model description can be found in supplementary material of this article and in (Fabian Scheller, 2018).

Model features

In the following table common model features are listed and explained and IRPopt's general feature spectrum is indicated:

Table 1: IRPopt model features

IRPopt	Model features	Explanation
x	Mathematical	Making use of mathematical language and concepts to design the model.
x	Conceptual	Composition of concepts which represent the most relevant parts of a system.
	Simulation	Input-Output relationship is analysed by choosing certain values for a set of decision variables e.g., based on predefined scenarios.
x	Optimization	An objective is minimized or maximized by finding the optimal values for a set of decision variables through solver algorithms.
	Linear programming	Only linear equations are involved.
	Nonlinear programming	At least one nonlinear equation is involved.
	Integer programming	All variables are integer numbers.
x	Mixed integer linear programming	At least one variable is integer and one isn't.
	Convex optimization	At least one convex function is involved.
	Static	Calculates system in equilibrium, it is time-invariant.
x	Dynamic	Model contains an element of time allowing the interaction between elements over time. Part of the input and output data are time series or functions over time.
x	Variable granularity	Extent to which a system is composed of distinguishable pieces e.g., km, m and mm can be adjusted.
x	Rolling horizon	Observation period is split into multiple optimization horizons. Typically, only a part e.g., half of the results of the first horizon is stored.
x	Discrete	Model is based on discrete data which can only take on a countable set of values.
	Continuous	Model is based on continuous data which can take on infinite values in between any two values. In general differential equations are used for these models.
x	Deterministic	Everything can be predicted with 100 % certainty. Same input means same output.
	Probabilistic	Incorporation of random variables and probability distributions lead to a probability distribution as a solution.
x	Explicit	All input parameters are known with which the output parameters can be calculated.
	Implicit	Output parameters are known and allow calculation of the input parameters.
x	Whitebox	Inner structure of the model is known and most of the times abstracted.
	Blackbox	Inner structure of the model is unknown. Only the input/output effects but not the chain of causes are observable.
	Greybox	Combination of White- and Blackbox Model.
x	Economic dispatch	The optimal operation/dispatch of flows between units within a system is determined.
x	Unit Commitment	The optimal on/off status of units within a system is determined.
	Investment decision	The optimal composition of a system/investment into system elements is analysed.

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Objective function

The overall objective of IRPopt is to maximize profit. Equation (4) shows the objective function. Within the brackets, energy flows $\mathfrak{e}$ are multiplied with energy tariffs $\mathfrak{w}$. This is done over each time step $\mathfrak{t} \in T$, each relevant system graph links (energy connections) $\mathfrak{a} \in A$ and over each market actor $s \in S$. The subset $\mathfrak{s}', \mathfrak{s}$ is about the constellation of the market actor who sends energy $\mathfrak{s}$ and the market actor who receives energy $\mathfrak{s}'$. The minuend takes the energy flow $\mathfrak{e}$ in time step $\mathfrak{t}$ in energy connection $\mathfrak{a}$ and multiplies it with the energy tariff $\mathfrak{w}$ in time step $\mathfrak{t}$ in energy connection $\mathfrak{a}$ for an energy source with the optimization hierarchy on the side of market actor $\mathfrak{s}$ to all energy sinks with the optimization hierarchy on the side of market actors $\mathfrak{s}'$. The subtrahend does the same for all energy sources with the optimization hierarchy on the side of market actors $\mathfrak{s}'$ to all energy sinks with the optimization hierarchy on the side of the market actor $\mathfrak{s}$.

$$\text{maximize} \quad \mathfrak{f}^{energy} \tag{1}$$

$$\text{subject to} \quad \mathfrak{g} = 0 \tag{2}$$

$$\mathfrak{h} \geq 0 \tag{3}$$

$$\underset{\mathfrak{e}}{maximize} \quad \mathfrak{f}^{energy} = \sum_{t \in T'} \sum_{s \in S'} \sum_{a \in A^s} \left(\sum_{s' \in S} \mathfrak{e}_{\mathfrak{t},\mathfrak{a}} \cdot \mathfrak{w}_{\mathfrak{t},\mathfrak{a},\mathfrak{s}',\mathfrak{s}} - \sum_{s' \in S} \mathfrak{e}_{\mathfrak{t},\mathfrak{a}} \cdot \mathfrak{w}_{\mathfrak{t},\mathfrak{a},\mathfrak{s},\mathfrak{s}'} \right) \tag{4}$$

Exemplary model embedment

Figure 1 conceptually visualizes the model embedment and the input/output data stream of IRPopt including the input data stream of another model MICOES-Europe. The input data specification over different scenarios and over the sensitivity analysis is introduced in a following section. MICOES-Europe uses the main input parameters country specific electricity demand, power plant fleet, fuel- and CO_2 prices and renewable electricity production to model day- ahead electricity spot prices and CO_2 emission intensities. These are fed into IRPopt. Further data comes from a created techno-economic database which includes empirical and literature-based data, for example of the chlorine demand profile or electrolyzer specification of the CAE. The input data is fed through a web-based frontend to the backend where data is pre-processed before it is sent further to the GAMS model which utilizes the IBM CPLEX solver. The resulting raw output data in GDX format contains more than 100 variables and more than 1000 parameters, most of them distributed over sets dependent on the temporal granularity in this work either hourly or quarter-hourly (8760 or 35040 steps). Over the front- and backend an upgraded data export tool is used for exporting the relevant output data elements from the raw GDX files. The relevant output data is further evaluated, for example, by calculating relative differences between scenarios or the result sensitivity. The key performance indicators in this work are electricity costs and CO_2 emissions, which are compared over different scenarios or sensitivity cases and result in potential savings through load shifting.

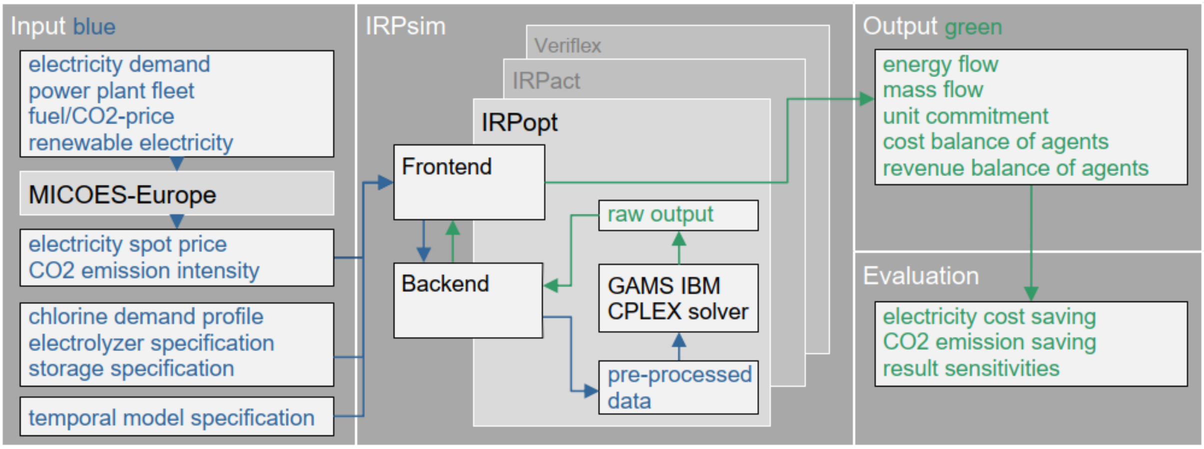


Figure 1: Exemplary model embedment for the H2-Flex use case

Energy sytem models - background

Finding innovative system solutions for sustainable municipalities is important to reach the national targets for decarbonisation to tackle climate change. The identification of such strategies is challenging for the decision maker since a variety of factors that point to the trends need to be taken into consideration. This applies amongst other things for the current business portfolio, the technological progress, the actor base, the regulatory framework as well as the market status. Given the complexity of these environments, system inter-dependencies and interactions between different alternatives need to be considered to systematically develop suitable strategies. One possibility to support decision makers is to apply energy system optimization models (ESOMs). Even though the methodology is widely recognized to generate economically optimal insights that inform energy and environmental policies regarding various public interest issues, the application of optimization-based models to municipalities is limited. Since research findings might be influenced by an entire range of factors, rather holistic frameworks and profound models are needed to sufficiently map the system complexities at the municipal level (see F. Scheller, T. Bruckner: Energy system optimization at the municipal level: An analysis of modelling approaches and challenges. Renewable and Sustainable Energy Reviews 105 (2019) 444–461).

Depending on the operational purpose, system models can serve different planning issues like design determinations and operation scheduling. While in the first case, the composition and dimensioning of the plant facilities for a particular area are specified, in the second case the operational mode of the plant facilities is predetermined for a predefined structure area. The choice of a suitable underlying methodology frequently follows an analytical approach. Commonly used methodologies are: (a) econometric, (b) macroeconomic, (c) economic equilibrium, (d) optimization, (e) simulation, (f) spreadsheet, (g) back casting and (h) multicriteria. Although, there are exceptions, the methodologies mentioned first (a–c) are usually applied to top-down models, the methodologies mentioned second (d–g) are generally applied to bottom-up models. At the level of concrete models, an additional distinction of ESOMs can be made regarding the mathematical class. Commonly applied techniques include linear programming (LP), mixed integer programming (MIP), dynamic programming (DP), and nonlinear programming (NLP). The modelling complexity but also the computational effort increases from the first-mentioned to the last-mentioned mathematical class. Concerning this matter LP and MIP models are the most widely used.

Since IRPopt focuses on optimization-based decision support as well as municipal entities and dynamics modelling, selected existing modelling tools are presented for this reported as follows:

• deeco	Dynamic Energy, Emission, and Cost Optimization model
• xeona	Extensible Entity-Oriented Optimization-Based Network-Mediated Analysis model
• DER-CAM	Distributed Energy Resources Customer Adoption Model, EnergyHub Model
• urbs	Urban Research Toolbox: Energy Systems Model
• MMESD	Multi-Modal On-Site Energy System Design Model
• RE^{3}ASON	Renewable Energies and Energy Efficiency Analysis System Optimization

deeco is defined as a decision support system for the planning and development of regional utility concepts given a predetermined, fluctuating energy demand. Through the optimal combination of conventional energy supply technologies and technologies employing regenerative energy sources possible savings of primary energy, emissions, and monetary costs might be quantified. LP is applied within a time-local quasi-dynamic recursive optimization scheme over a period of one representative year. *Xeona* combines high-resolution modelling with multi-agent simulation and thus extends the pre-existing technology-centred *deeco* approach with controllers, markets, actors, and proactive policy measures that exist in reality or are under consideration. In this context, the ESOM can capture multi-participant domestic and commercial behaviour rather than posit a single system actor who makes universally optimal choices centralized planner as most of the existing ESOMs do. DER-CAM represents an economic and environmental MIP that has been in development by Michael Stadler and the Microgrid Team at the Berkeley Lab since the early 2000s. It is an advanced, deterministic optimization tool for obtaining the best investment decisions. It regards the design and the operation of residential or commercial sites by considering multiple energy carrier microgrids while co-optimizing multiple stacked value streams that include load shifting, peak shaving, power export agreements, or participation in ancillary service markets. The bottom up ESOM is intended for utilities, research institutions, and industrial companies and has been largely applied to different problems with respective necessary enhancements. The *EnergyHub* is a unit that provides the basic features in- and output, conversion, and storage of different energy carriers. Thus, the concept is a multi-generation system in which production, transmission, storage and consumption of multi-energy carriers take place to meet different type of demands. The main sectors are electricity, heat, and gas. *urbs* represents an ESOM for multi-commodity energy systems with a focus on optimal storage sizing and utilization. It finds the minimum cost energy system to satisfy given demand time series for possibly multiple commodities. The consumption and generation amount of the various processes is defined by a constant input and output ratio. The aim of *MMESD* is to develop an energy system design method, which is capable of minimizing total expenditures encountered for the energy supply system at a particular site by selecting the best energy technologies, sizing their capacity and choosing their best operating strategy. It is mostly suited for newly constructed (Greenfield project) or expanded (Brownfield project) sites as large building complexes, such as airports or university campuses. The outcome of the energy system design method is a preliminary design of the energy system which needs to be post-processed and examined for its feasibility. Data collection for an explicit city or district is very time-consuming, and in many cases, limited by privacy protection issues. The RE^{3}ASON model almost exclusively includes publicly available data from Open Street Map and Bing maps, augmented by location-specific data from the user. The add-on represents an automated approach for the geographically anchored estimation of demand structures, rooftop PV potential as well as wind or biomass potential estimation. Thereby, underlying electricity and heating network topology is not modelled. Furthermore, large scale processes of power plants are not considered.

The selected ESOMs already cover a wide range of required system characteristics. In view of the results of our analysis conducted, IRPopt particularly addresses the following key issues that need to be considered for an advanced ESOMs: integrated view, business modelling, spatial planning, complexity level, temporal resolution and uncertainty analysis. Thus, individual households, neighbourhood communities, organizational units and market institutions represent major system drivers and should be modelled separately, so that an integrated view of supply and demand side is necessary for optimal investigation of the interaction at the municipal level. Due to the importance and still low monetary potential of certain existing renewable solutions, the legislator often encourages their implementation. Capitalizing on these benefits, however, is only feasible under compliance with the regulatory frameworks, market mechanisms and technological capabilities. For IRPopt, we implemented the corresponding market principles pertaining to decentralization, flexibilization, and virtualization. However, they are important in fully assessing decentralized business model synergy and competition effects at the municipal level, especially in comparison with centralized business models.

2. IRPOPT USE CASES

2.1 Community electricity storage systems

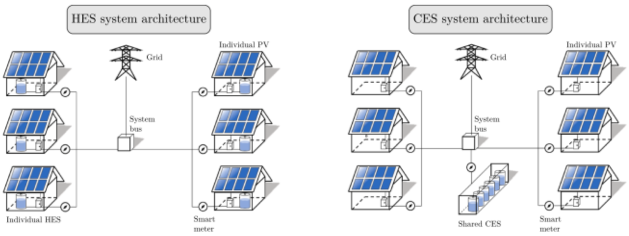
Goal

Economic assessment of community electricity storage systems in combination with PV and consideration of competitive flexibility options.

Method

Techno-economic modelling of cost-optimal operation of different competing residential flexibility options.

System



HES = Household Electricity Storage
CES = Community Electricity Storage

Indicator

- Equivalent annual value (EAV, positive = beneficial) in €.
- Storage capacity reduction through applying community instead of household electricity storage systems in %.
- Cost coverage of an optimal community electricity storage system in %.

Scenarios

Each one in combination with HES and CES:

1. Base
2. Heat pump
3. Demand response (DR)
4. Heat pump and DR
5. Power-to-Energy

Keywords

- Demand-side flexibility
- Demand response
- Sector coupling
- Storage systems
- Optimization modelling
- Energy transition

Publication

(Fabian Scheller et al., 2020)

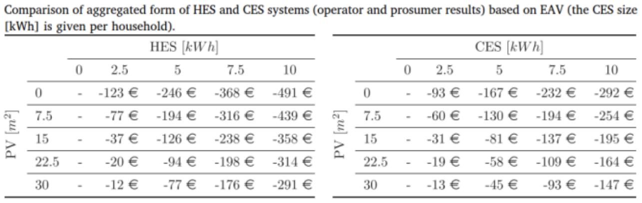
Applied Energy

Competition between simultaneous demand-side flexibility options: the case of community electricity storage systems

Fabian Scheller, Robert Burkhardt, Robert Schwarzeit, Russell McKenna, Thomas Bruckner

Results

Equivalent annual value



Comparison of aggregated form of HES and CES systems (operator and prosumer results) based on EAV (the CES size [kWh] is given per household).

PV $[m^2]$	HES $[kWh]$ 0	2.5	5	7.5	10
0	-	-123 €	-246 €	-368 €	-491 €
7.5	-	-77 €	-194 €	-316 €	-439 €
15	-	-37 €	-126 €	-238 €	-358 €
22.5	-	-20 €	-94 €	-198 €	-314 €
30	-	-12 €	-77 €	-176 €	-291 €

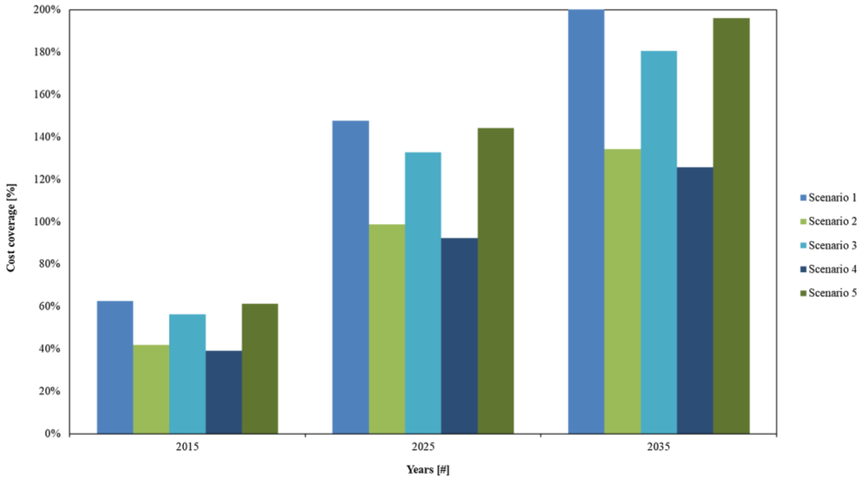
PV $[m^2]$	CES $[kWh]$ 0	2.5	5	7.5	10
0	-	-93 €	-167 €	-232 €	-292 €
7.5	-	-60 €	-130 €	-194 €	-254 €
15	-	-31 €	-81 €	-137 €	-195 €
22.5	-	-19 €	-58 €	-109 €	-164 €
30	-	-13 €	-45 €	-93 €	-147 €

Storage capacity reduction

Through applying community instead of household electricity storage system:

1. Base: 8%
2. Heat pump: 19%
3. Demand response (DR): 11%
4. Heat pump and DR: 23%
5. Power-to-Energy: 9%

Cost coverage

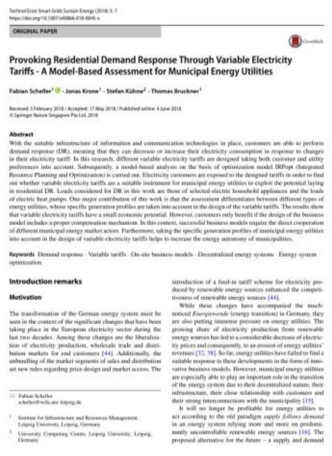


Highlights

- 9% storage capacity reduction on average through applying CES instead of HES.
- Losses due to simultaneous application of flexibility options outweigh the benefits.
- Sector coupling constitutes a greater competition factor than demand response.
- Community storage systems will become economically profitable in the next few years.

Table 2: Use Case: Community electricity storage systems

2.2 Residential Demand Response

Goal	Economic assessment of residential demand response through variable electricity tariffs from the perspective of municipal energy utilities.	**Keywords**
Method	Techno-economic modelling of cost optimal residential load shifting over different variable electricity tariffs and heat pump availability.	• Demand response • Variable tariffs • On-site business models • Decentralized energy systems • Energy system optimization
System	**Energy utilities:** Low-priced orchestrator (LO): without any own generation facilities. Green municipal utility (GMU): with own wind energy plants. Conventional municipal utility (CMU): with own cogeneration plants. **Residential customers:** Customer group 1 (CG1): five customers with distinct electrical load profiles without electrical heating. Customer group 2 (CG2): five customers with distinct electrical load profiles with electrical heating (heat pump). **Variable electricity tariffs:** 7 different tariffs including one flat tariff.	**Publication** (Fabian Scheller, Krone, et al., 2018)  Technol Econ Smart Grids Sustain Energy (2018) 3: 7 https://doi.org/10.1007/s40866-018-0045-x ORIGINAL PAPER Provoking Residential Demand Response Through Variable Electricity Tariffs - A Model-Based Assessment for Municipal Energy Utilities Fabian Scheller[1] · Jonas Krone[1] · Stefan Kühne[2] · Thomas Bruckner[1] Received: 5 February 2018 / Accepted: 17 May 2018 / Published online: 4 June 2018 © Springer Nature Singapore Pte Ltd. 2018 Abstract With the suitable infrastructure of information and communication technologies in place, customers are able to perform demand response (DR), meaning that they can decrease or increase their electricity consumption in response to changes in their electricity tariff. In this research, different variable electricity tariffs are designed taking both customer and utility preferences into account. Subsequently, a model-based analysis on the basis of optimization model IRPopt (Integrated Resource Planning and Optimization) is carried out. Electricity customers are exposed to the designed tariffs in order to find out whether variable electricity tariffs are a suitable instrument for municipal energy utilities to exploit the potential laying in residential DR. Loads considered for DR in this work are those of selected electric household appliances and the loads of electric heat pumps. One major contribution of this work is that the assessment differentiates between different types of energy utilities, whose specific generation profiles are taken into account in the design of the variable tariffs. The results show that variable electricity tariffs have a small economic potential. However, customers only benefit if the design of the business model includes a proper compensation mechanism. In this context, successful business models require the direct cooperation of different municipal energy market actors. Furthermore, taking the specific generation profiles of municipal energy utilities into account in the design of variable electricity tariffs helps to increase the energy autonomy of municipalities.
Indicator	• Change in earnings over customer groups and utility types in €	
Scenario	• 7 tariffs (1 flat, 6 variable) over • 2 customer groups (heat pump: CG1: no, CG2: yes) over • 3 utilities (own generation: LO: none, GMU: wind, CMU: cogeneration)	
Sensitivity	• 5 load shifting temporal horizons (1-3h) • 5 load shifting capacity shares of total load (10-30%)	

Results

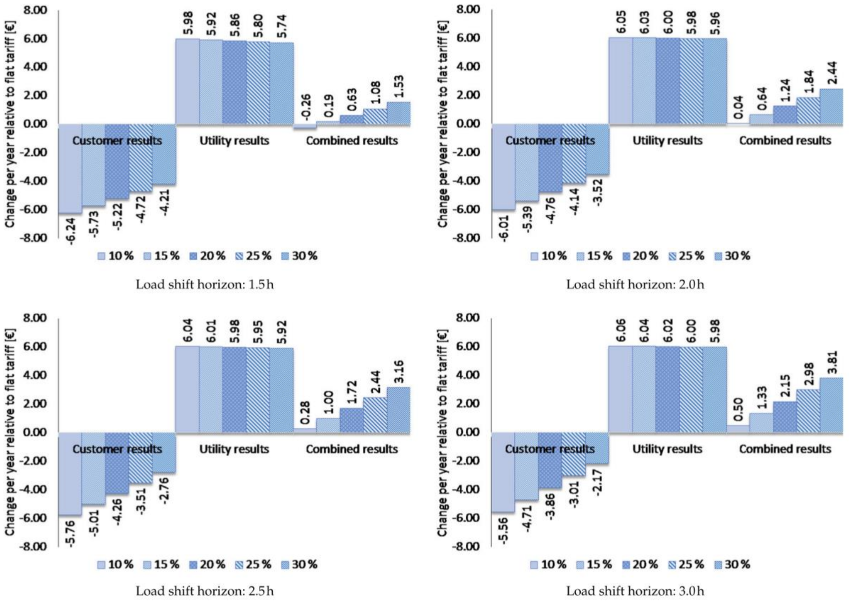
Change in earnings	**Highlights**
 Load shift horizon: 1.5h Load shift horizon: 2.0h Load shift horizon: 2.5h Load shift horizon: 3.0h **Fig. 6** Change in customer, utility and combined results in 2015 when applying tariff 1h$_{dyn}$ compared to a FT for varying load shift horizons and shares of total shiftable load of 10 - 30 % 1hdyn: Tariff with hourly changes in price (hourly avg. of spot prices + margin)	• For the considered tariffs, customers profit while utilities pay extra. • Customers and utilities combined end up with a small profit. • Variable electricity tariffs have a small economic potential.

Table 3: Use Case: Residential Demand Response

2.3 Decentralized energy business models

Goal

Determine the profitability, affordability, autarky and ecology of 5 decentralized business models for energy provision at a neighbourhood energy system level with 5 different energy conversion technologies including one storage.

Method

Techno-economic modelling of cost-optimal operation of different energy converting or storing technology portfolios within the framework of 5 business models.

System

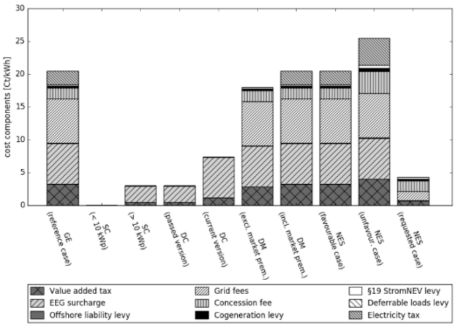


Fig. 1. Business model cost components

	#0	#1	#2	#3
Pros. 1	EG, FG, NGB	PV, EG, FG, NGB	PV, EG, FG, NGB	PV, EG, HG
Pros. 2	EG, FG, NGB	EG, FG, NGB	EG, HP	EG, HG
Utility				CHP

Business models

SC = Self consumption
DC = Direct consumption
DM = Regional direct marketing
NES = neighbourhood energy storage system
GC= Grid coverage

Technology portfolio

PV = Photovoltaic
HP = Heat pump
ES = Electrical storage
NGB = Natural gas boiler
CHP = Combined heat power
Pros. = Prosumer

Indicator

- Profitability, affordability, autarky and ecology levels in % or classes (+ positive, o neutral, - negative)

Scenarios

- 5 energy business models over
- 4 technology portfolios built of 5 energy conversion technologies over
- 2 Prosumers, 1 utility

Keywords

- energy business models
- decentralized energy technology
- energy system modelling
- system optimization

Publication

(Fabian Scheller et al., 2017)

Effects of Implementing Decentralized Business Models at a Neighborhood Energy System Level: A Model Based Cross-sectional Analysis

Fabian Scheller*†, David G. Reichelt‡, Steffen Dienst‡, Simon Johanning†, Sören Reichardt†, Thomas Bruckner†

Results

Profitability, affordability, autarky and ecology levels

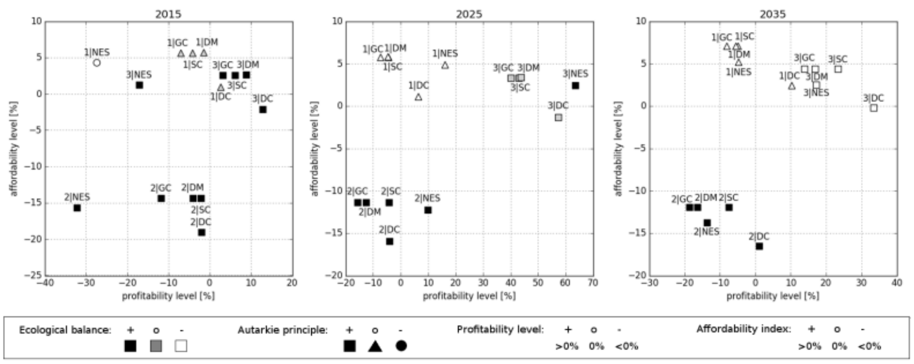


Fig. 4. Decentralized business model comparison at neighborhood level in reference to case #0

Affordability index: Relative change of consumer cost compared to reference case.
Profitability level: Relative change in utility profit compared to reference case.
Ecological balance: Produced CO2 emissions to cover demand in respective time steps.
Autarky principles: Ratio of local produced and consumed energy and the overall electricity consumption.

Highlights

- Profitability, affordability, autarky and ecology levels significantly varies between business cases, year and technology portfolio.
- Different business models influence the demand behaviour and renewables integration.

Table 4: Use Case: Decentralized energy business models

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2.4 H2-Flex

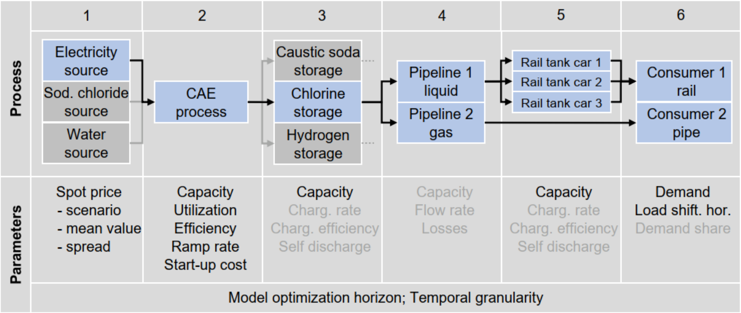
Goal

Determine the potential electricity cost and CO_2 savings for a chlor-alkali electrolysis through an optimal application of load shifting for the actual but also calculated future electricity prices.

Method

Modelling the cost optimal operation of a chlorine value chain based on a real case study in Germany and over different scenarios and sensitivities.

System



Indicator

- Electricity cost savings compared to reference cases in % and €
- CO_2 emission savings compared to reference cases in % and tCO_2

Scenarios

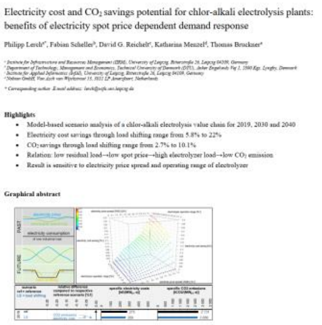
14 scenarios over the years 2019, 2030 and 2040; scenarios based on different electricity spot prices and CO_2 emission intensities which result from different total electricity demand, renewable electricity supply and CO_2 price.

Keywords

- Demand response
- Load shifting
- Chlor-alkali-electrolysis
- Electricity cost savings
- CO_2 emission reduction

Publication

(Lerch et al. 2022 Work. paper)



Electricity cost and CO_2 savings potential for chlor-alkali electrolysis plants: benefits of electricity spot price dependent demand response

Philipp Lerch[a*], Fabian Scheller[b], David G. Reichelt[c], Katharina Menzel[d], Thomas Bruckner[a]

Highlights

- Model-based scenario analysis of a chlor-alkali electrolysis value chain for 2019, 2030 and 2040
- Electricity cost savings through load shifting range from 5.8% to 22%
- CO_2 savings through load shifting range from 2.7% to 10.1%
- Relation: low residual load→low spot price→high electrolyzer load→low CO_2 emission
- Result is sensitive to electricity price spread and operating range of electrolyzer

Graphical abstract

Results

Interrelation

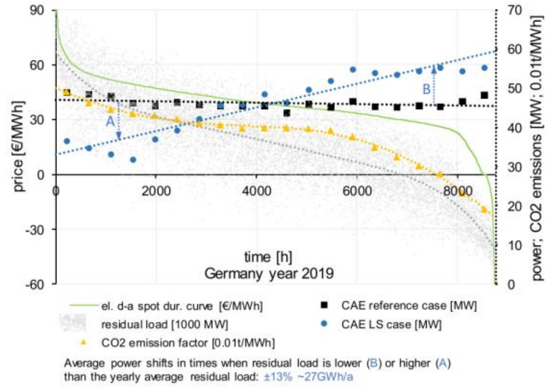


Figure 7: Interrelation of residual load, electricity prices and CAE load profile

Sensitivity

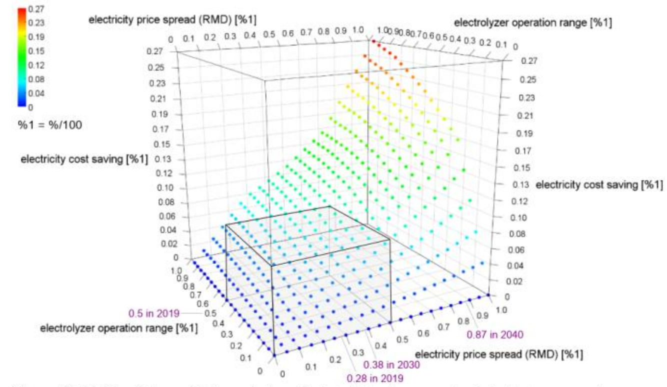


Figure 10: Multivariate sensitivity analysis with electricity price spread and electrolyzer operation range

Electricity cost and CO_2 savings

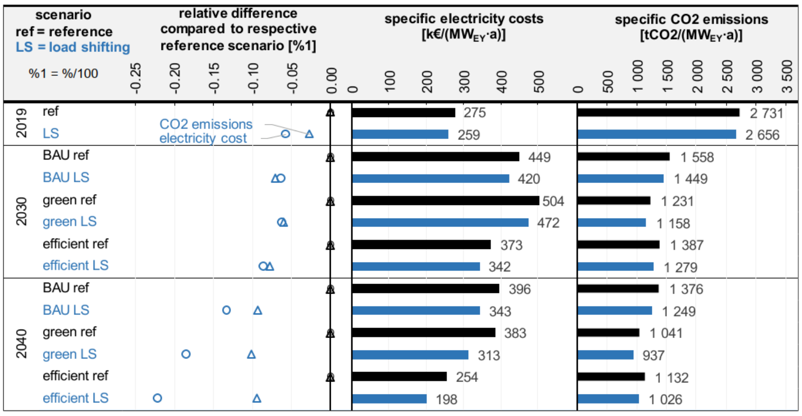


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Table 5: Use Case: H2-Flex

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 864242
Topic: LC-SC3-SCC-1-2018-2019-2020: Smart Cities and Communities

2.5 HYPOS-Speicherstudie

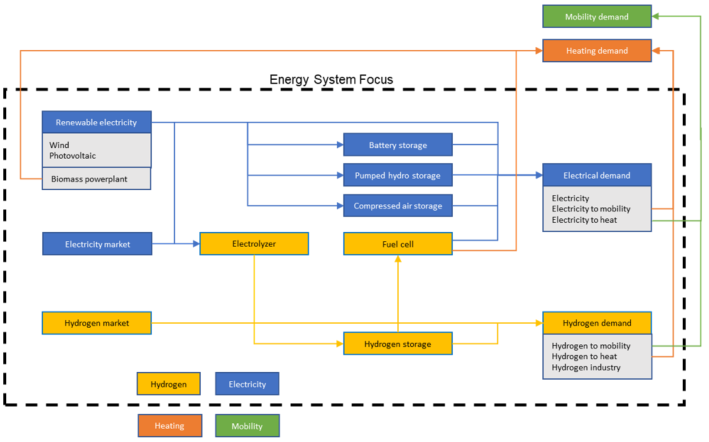
Goal

Analysis of future hydrogen storage needs and potentials in Germany for a climate-neutral energy system.

Method

Modelling the cost optimal operation of energy conversion units and storages to meet future electricity and hydrogen demand.

System



Indicator

- Hydrogen storage capacity needs in TWh
- Hydrogen storage energy throughput in TWh/a

Scenarios

3 scenarios based on different assumptions for future renewable electricity generation and weather events by including a dark doldrum period.

Keywords

- Storage
- Hydrogen
- Energy transition
- Economic dispatch model
- Salt caverns

Publication

(Kondziella et al. 2022 Work. paper)

Title: The techno-economic potential of large-scale hydrogen storage in Germany for a climate-neutral energy system

Authors: Kondziella, Hendrik[1,*]; Specht, Karl[1]; Scheller, Fabian[2]; Lerch, Philipp[1]; Bruckner, Thomas[1]

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[2]Energy Economics and Modelling, Department of Technology, Management and Economics, Technical University of Denmark (DTU), Produktionstorvet, 424, 013, 2800 Kgs. Lyngby, Denmark

Highlights:

- Quantification of uncertainty regarding large-scale hydrogen storage in the German energy system of 2045.
- The sensitivity analysis of an economic dispatch model was executed 192 times.
- Need for hydrogen storage capacity peaks at 67 TWh_{H2} and energy throughput at 190 TWh_{H2}.
- Main drivers are hydrogen import options, electrolyzer capacity and hydrogen demand.

Abstract:

Recent climate protection scenarios project a significant demand for hydrogen as energy carrier, and feedstock for the industry. This makes hydrogen a viable alternative where carbon-free electricity cannot be used. One component of the value chain for the provision of hydrogen is its storage. The seasonal storage of a gas-based energy carrier is a recognized and reliable technology in the energy industry. Salt caverns are particularly suitable for the storage of hydrogen. Germany exhibits a high potential for expanding cavern storage capacity, which corresponds to many times the expected demand for hydrogen. In view of the expected long-term decline in fossil natural gas use, the question arises as to whether existing caverns will be able to meet future storage needs. To this end, we present a model that determines the operation of generation and storage units to meet electricity and hydrogen demand in a cost-optimal manner. The basic framework for the plant fleet is derived from comprehensive capacity expansion models found in the literature. Our analysis focuses on the use of hydrogen storage in terms of energy throughput and maximum storage capacity. We contribute to a broadening of the research state by evaluating key input parameters of the future energy system. Based on 192 model runs, the sensitivity analysis shows the range of uncertainty in terms of storage use. The results reflect, that the systemic and the economic value of the hydrogen storage strongly depends on the boundary conditions, given, e.g., by the hydrogen demand profile or the electrolyzer capacity. The uncertainty ranges from 0 to 67 TWh_{H2} for the storage capacity, and 0 to 190 TWh_{H2} for the annual energy throughput which corresponds to the order of magnitude of existing cavern capacities. Nonetheless, the higher utilization of the salt caverns in terms of full cycles per year due to the variable operation of electrolyzers needs to be further analyzed with regards to geologic permissibility. In this way, the results are significant for gas storage operators for deriving a transformation strategy and policy makers to evaluate potential financial funding requirements.

Keywords:

storage, hydrogen, energy transition, economic dispatch model, salt caverns

Word count (main text): 9144

* = corresponding author details, kondziella@wifa.uni-leipzig.de

Results

Hydrogen storage capacity needs and energy throughput

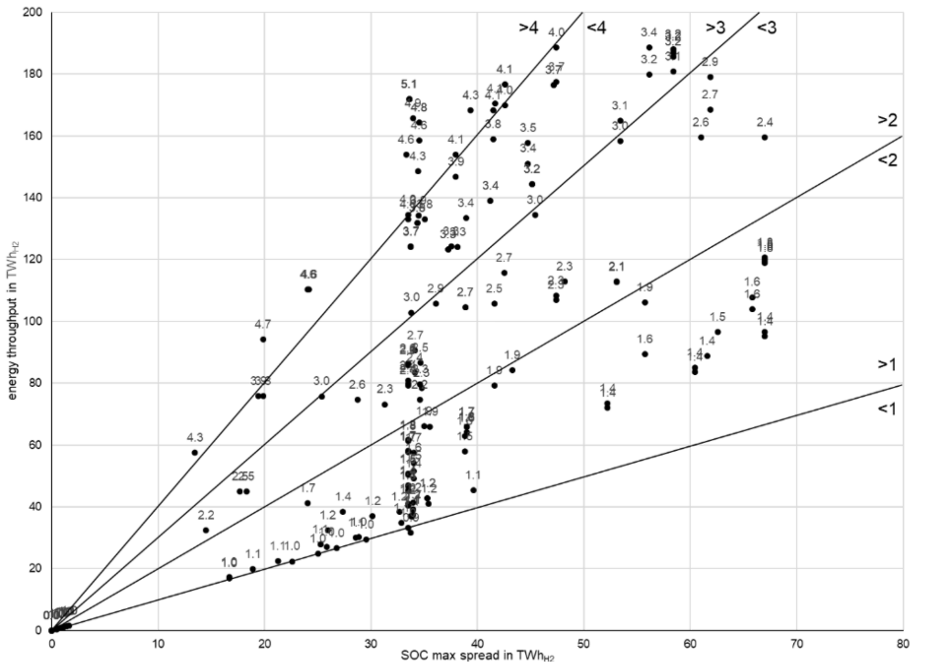

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Table 6: Use Case: HYPOS-Speicherstudie

3. MODEL DEVELOPMENT – FURTHER READINGS

Year	Citation	Title
2021	(Reichelt et al., 2021)	Towards an Infrastructure for Energy Model Computation and Linkage
2019	(Fabian Scheller & Bruckner, 2019a)	Energy system optimisation at the municipal level: An analysis of modelling approaches and challenges
2019	(Kühne, Scheller, Kondziella, Reichelt, & Bruckner, 2019)	Decision support system for municipal energy utilities: approach, architecture
2019	(Fabian Scheller & Bruckner, 2019b)	Entity-Oriented Multi-Level Energy System Optimization Modelling
2018	(Fabian Scheller, Burgenmeister, et al., 2018)	Towards integrated multi-modal municipal energy systems: An actor-oriented optimisation approach

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Reichelt, D. G., Kühne, S., Scheller, F., Abitz, D., & Johanning, S. (2021). Towards an Infrastructure for Energy Model Computation and Linkage. *INFORMATIK 2020. Gesellschaft Für Informatik*, 225–235. https://doi.org/10.18420/inf2020_21

Scheller, Fabian;, & Reichelt, D.-G. (2022). *GitHub - IRPsim/IRPopt*. Retrieved from https://github.com/IRPsim/IRPopt

Scheller, Fabian. (2018). *Modeling and Optimizing of Integrated Multi-Modal Energy Systems for Municipal Energy Utilities*. University of Leipzig.

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Scheller, Fabian, & Bruckner, T. (2019b). *Entity-Oriented Multi-Level Energy System Optimization Modeling*. 191–197. https://doi.org/10.1007/978-3-030-18500-8_25

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Scheller, Fabian, Reichelt, D. G., Dienst, S., Johanning, S., Reichardt, S., & Bruckner, T. (2017). Effects of implementing decentralized business models at a neighborhood energy system level: A model based cross-sectoral analysis. *International Conference on the European Energy Market, EEM*. https://doi.org/10.1109/EEM.2017.7981910

APPENDICES

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