Energy Hub Gas: A Multi-Domain System Modelling and Co-Simulation Approach

Rafael Poppenborg
Karlsruhe Institute of Technology, Institute for Automation and Applied Informatics
Karlsruhe, Germany
rafael.poppenborg@kit.edu

Johannes Ruf
DVGW-Research Centre at Engler-Bunte-Institute of Karlsruhe Institute of Technology
Karlsruhe, Germany
johannes.ruf@alumni.kit.edu

Malte Chlosta
Karlsruhe Institute of Technology, Institute for Automation and Applied Informatics
Karlsruhe, Germany
malte.chlosta@partner.kit.edu

Jianlei Liu
Karlsruhe Institute of Technology, Institute for Automation and Applied Informatics
Karlsruhe, Germany
jianlei.liu@kit.edu

Christian Hotz
DVGW-Research Centre at Engler-Bunte-Institute of Karlsruhe Institute of Technology
Karlsruhe, Germany
hotz@dvgw-ebi.de

Clemens Düpmeier
Karlsruhe Institute of Technology, Institute for Automation and Applied Informatics
Karlsruhe, Germany
clemens.duepmeier@kit.edu

Thomas Kolb
DVGW-Research Centre at Engler-Bunte-Institute of Karlsruhe Institute of Technology and Karlsruhe Institute of Technology, Engler-Bunte-Institute, Division of Fuel Technology
Karlsruhe, Germany
thomas.kolb@kit.edu

Veit Hagenmeyer
Karlsruhe Institute of Technology, Institute for Automation and Applied Informatics
Karlsruhe, Germany
veit.hagenmeyer@kit.edu

ABSTRACT

Coping with the complexity of future energy grids and the rising challenges of the energy transition to more renewable energy sources (RES), an Energy Hub Gas (EHG) concept appears to be a promising approach. This concept combines various technical components to a sector-coupling system network to support the electricity grid with ancillary and balancing services to cope with the fluctuating generation by RES and to provide (renewable) energy carriers. Additionally, the EHG serves as regional gateway and as a converter for large, centralized RES-feed-in and aggregation/distribution hub of local RES-feed-in. For combining several separate models from different domains to an EHG system model, a co-simulation approach is used with high regard on flexibility concerning the modelling aspects as well as high modularity to easily adapt the concept to further use cases. As main results presented in the paper, the coherence of the extended EHG system model and its usability for implementation in co-simulation can be shown in first simulations.

MCPES'21, May 19–21, 2021, Nashville, TN, USA

ACM ISBN 978-1-4503-8608-1/21/05.
https://doi.org/10.1145/3470481.3472712

CCS CONCEPTS

• **Hardware** → **Renewable energy**; **Power conversion**; **Smart grid**.

KEYWORDS

hybrid modeling and simulation, co-simulation, multi-domain systems, cyber-physical energy systems

ACM Reference Format:
Rafael Poppenborg, Johannes Ruf, Malte Chlosta, Jianlei Liu, Christian Hotz, Clemens Düpmeier, Thomas Kolb, and Veit Hagenmeyer. 2021. Energy Hub Gas: A Multi-Domain System Modelling and Co-Simulation Approach. In *9th Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MCPES'21), May 19–21, 2021, Nashville, TN, USA.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3470481.3472712

1 INTRODUCTION

The energy transition in the European Union and especially in Germany rises the need for installing and integrating more renewable energy sources (RES) into existing infrastructures that are step by step adapted. The volatile generation of this distributed generation units increase the challenge of secure energy supply. Additionally, new technologies such as electrification of the transport sector will further increase the volatility of load. Furthermore, changes in the grid topology transforming a grid from uni-directional to bi-directional energy flow adding local fluctuating and non-steerable generation of RES in distribution networks is a major challenge.

One approach to address this is adding local flexible energy resources, e.g. realized by the Energy Hub (EH) concept [3], to the power network compensating part of local fluctuations. The Energy Hub Gas (EHG) depicted in figure 1 is designed as a sector coupling plant network that offers flexibility to the electricity grid operator by storing generation peaks from RES as well as reacting to load peaks from the demand side with own generation. The flexibility of the EHG allows taming fluctuating generation and load and makes it more controllable. This is one approach to achieve an increasing integration of already existing RES as well as open up opportunities for installing new RES more rapidly. The presented EHG stands for an alternative vision to most-electric world and extensive electrification across all demand sectors. It serves as regional gateway for renewable energy (electrons) to meet local demand of all energy forms and carriers (electrons and molecules).

The presented paper introduces basic concepts and a first implementation of a system simulation model of the mentioned cyber physical energy system (CPES) for evaluating the usability of such a solution for the future. While an integrated Energy Management System (EMS) as well as an appropriate optimization method will be mandatory components for operating the CPES in reasonable ways, this paper will focus on the basic components of the model and their integration towards a system model. Operational strategies will then be presented in future work.

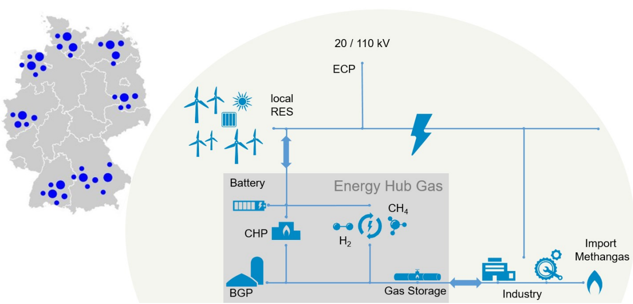

Figure 1: Energy Hub Gas system overview

The paper is organized as follows: section II outlines the related work about the co-simulation concepts and the EH approach. Section III describes the used methodology concerning the simulation setup and the use case, followed by section IV introducing a detailed look at component models. Section V discusses the obtained results. The paper ends with a conclusion section VI and an outlook for future research within the field of the EH approach and CPESs.

2 RELATED WORK

In the following section, a brief overview about the related work in the field of co-simulation and cyber physical energy system (CPES) simulation is given to set our approach for system modelling in relation to existing work.

2.1 Co-Simulation Frameworks

For simulating and evaluating Energy Hub Gas (EHG) use cases, the use of co-simulation frameworks are eligible solutions. There is abundant and vast literature proposing various kinds of co-simulation approaches that can be used to model, simulate, and evaluate complex systems such as Smart Grids. Due to the interdisciplinarity needed for modelling each component of a complex sector-coupled energy system, various heterogeneous tools must be connected into a system simulation e.g. by use of a co-simulation approach. However, many co-simulation approaches are limited to particular scenarios. Moreover, they do not allow to integrate many different kinds of simulators that could provide a more universal co-simulation framework for simulating real complex multi-domain energy system models, such as the presented EHG use case consisting of multiple physical components and technical plants, energy carriers, IT communication, and control components.

Preliminary work [8] has shown the challenges of developing co-simulation frameworks that allow for the integration of (dynamic) plants, converters but also infrastructure models (electricity, gas, heat). Furthermore, there are also some co-simulation frameworks, e.g. Mosaik and the PROcess Operation Framework (PROOF), that are more flexible and allow to combine, and reuse a bigger number of existing component models executed in different simulator tools to create complex system models and execute Smart Grid scenarios:

2.1.1 Mosaik. As described in [9, 10], the Mosaik framework is designed as a flexible solution specifically for CPES/smart grids research with a focus on co-simulations across multiple domains. Its architecture consists of a simulator management module for configuring and integrating different component models implemented for different simulators by e.g. using Functional Mock-up Units (FMUs) and enabling data exchange between the simulators, and a scheduler acting as master for coordinating the execution steps and the exchange of data between simulations. For implementing their system model, mosaik offers two application programming interfaces (APIs) to system modellers:

- the component API that has to be implemented by users for connecting simulators to Mosaik,
- the scenario API for setting up co-simulation scenarios by using the Mosaik scheduler as a master for controlling data flow and execution of simulator operations according to a test scenario.

Note, that with Mosaik, modelers will model their system by writing programming code in Python using the Mosaik APIs.

2.1.2 Process Operation Framework. According to [4, 5], the PROOF is a generic, modular, and highly scalable framework that automates the startup, synchronization, and management of scientific computational workflows. By using container-automation, distributed message oriented middleware and a microservice-based architecture it enables novel distributed process execution and coordination. It also supports trans-disciplinary, multi-domain co-simulations as part of larger workflows including different simulation tools (e.g. Python, Matlab, FMU, Julia, Java, etc). Moreover, an easy-to-use web user interface is provided to allow system modelers to easily set up, perform and control workflows or co-simulations, which can be executed remotely on a computing cluster without the need to think about the underlying computing infrastructure as an execution environment.

While the integration of different simulator types and tools within PROOF needs some programming effort for setting up the tools as reusable building blocks for creating workflows and system simulations, the setup of a system model itself is done using a graphical editor in a declarative way. PROOF is also part of a larger ecosystem where scenario data can directly fetched from different data sources and injected into a simulation workflow. Output and intermediate results can be written to data storage on the cluster and e.g. visualized in dashboards.

2.2 The Energy Hub Approach

Transformation, conversion, and storage of various forms of energy in decentralized plant networks as flexibility resources called Energy Hub (EH) is a promising approach for smoothing out and balancing local generation and demand as stated in [6] especially if renewable energy sources (RES) are integrated. In [11] usage of the EH concept on an neighbourhood scale is proposed, which fits as one placement option for the presented use case. However, the EHG model described in the following is designed to serve not only for small neighbourhood uses cases but is also applicable to industrial areas as well as small cities and at interconnections to the transmission grid. The idea of an EH was first introduced by [3] and [2] in 2007 and is defined as following. EHs consist of multiple energy carriers, that can convert, condition and store multiple forms of energy. Formulated more abstract, they define a black box with energy inputs and an outputs of different types, which will be internally transformed between the different types and eventually stored for later use. Mathematically, the transformation process can be interpreted as an coefficient matrix H_{ab} that connects multiple Energy inputs I_ω to a number of Energy outputs O_σ.

A generic conversion formulation with multiple in- and outputs for a single unit can be described by three parts: power output vector L, the converter coupling matrix C, and the power input vector P. Both P and L merge all considered energy carriers $[\alpha, \beta, ..., \omega]$ e.g. [hydrogen, natural gas, ..., heat] into one vector. The coupling matrix C consists of all instrumented energy conversions $[\alpha, \beta, ..., \omega] \rightarrow [\alpha, \beta, ..., \omega]$, where the component $c_{\alpha\beta}$ converts α to β, e.g. hydrogen to natural gas. These connections can generically be formulated as:

$$\underbrace{\begin{pmatrix} L_\alpha \\ L_\beta \\ \vdots \\ L_\omega \end{pmatrix}}_{L} = \underbrace{\begin{bmatrix} c_{\alpha\alpha} & c_{\beta\alpha} & \cdots & c_{\omega\alpha} \\ c_{\alpha\beta} & c_{\beta\beta} & \cdots & c_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ c_{\alpha\omega} & c_{\beta\omega} & \cdots & c_{\omega\omega} \end{bmatrix}}_{C} \cdot \underbrace{\begin{pmatrix} P_\alpha \\ P_\beta \\ \vdots \\ P_\omega \end{pmatrix}}_{P} \tag{1}$$

The components $c_{\alpha\beta}$ of the coupling matrix C are called coupling coefficients and map in- to output power. $c_{\alpha\beta}$ can either convert between different energy carriers in the case of $\alpha \neq \beta$, or transmit one energy carrier to itself $\alpha = \beta$. In both cases, $c_{\alpha\beta}$ can be between 0 and 1, or equal to 1, making it a lossy or lossless conversion/transmission. The special case where $c_{\alpha\beta}$ is equal to 0 represents no coupling between given carriers.

C can be dependent on the power input or other factors, e.g. the control performed by an Energy Management System (EMS) on a conversion unit, therefore $C = f(P, t, ...)$, which results in general in non-linearity for C. Another important property of equation (1) is, that from two energy carriers on upwards it represents an under-determined system of equations. This results in C being not invertible. In other words, there is no unambiguous solution, and the coupling matrix can be optimized.

In [2], two important characteristics of the converter coupling matrix are stated, that can be summarized as

$$0 \leq \sum_{\beta \in \zeta} c_{\alpha\beta} \leq 1 \forall \alpha, \beta \in \zeta \subseteq \varepsilon. \tag{2}$$

The sum over any set ζ of ε must be larger than 0 but less or equal to 1, meaning that no energy conversion can increase the overall amount of energy available from the inputs.

Beside conversion, the energy storage needs special consideration. The desired hub can not only convert but also store energy over a certain time. The storage of energy results in time dependencies of all modelling variables. In [2], Geidel summarizes the storage influence on the total power output of an EH in the storage flow vector

$$M^{eq} = CQ + M. \tag{3}$$

In this representation Q is the storage power output before, and M the power output after an energy carrier was converted. Each component of M^{eq} can be restated as

$$M^{eq}_\beta = c_{\alpha\beta} Q_\alpha + M\beta = \frac{c_{\alpha\beta}}{e_\alpha} \dot{E}_\alpha + \frac{1}{e_\beta} \dot{E}_\beta, \tag{4}$$

with e_α, e_β the charging or discharging efficiencies for respective energy carrier, and $\dot{E}$ the change in energy of a energy carriers storage. The relationship between the total storage influence of storage units with respect to its change in energy can be formulated in matrix notation to fit the concept of the coupling matrix C as follows:

$$\underbrace{\begin{pmatrix} M^{eq}_\alpha \\ M^{eq}_\beta \\ \vdots \\ M^{eq}_\omega \end{pmatrix}}_{M^{eq}} = \underbrace{\begin{bmatrix} s_{\alpha\alpha} & s_{\beta\alpha} & \cdots & s_{\omega\alpha} \\ s_{\alpha\beta} & s_{\beta\beta} & \cdots & s_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ s_{\alpha\omega} & s_{\beta\omega} & \cdots & c_{\omega\omega} \end{bmatrix}}_{S} \cdot \underbrace{\begin{pmatrix} \dot{E}_\alpha \\ \dot{E}_\beta \\ \vdots \\ \dot{E}_\omega \end{pmatrix}}_{\dot{E}} \tag{5}$$

thereby representing the complete EHs output power as

$$L = CP - S\dot{E} = [C \ -S] \begin{bmatrix} P \\ \dot{E} \end{bmatrix} \tag{6}$$

3 BASIC CONCEPT FOR SYSTEM MODEL IMPLEMENTATION

The presented Energy Hub Gas (EHG) integrates various technical plants for energy storage and conversion between different energy carriers as mentioned in the previous section. According to the mathematical model presented in the previous section, the basic energy flows through the system can be described by the given matrix formulas. Beside this, the system model must also incorporate IT components for controlling the behavior of the conversion and storage units over time by an Energy Management System (EMS) as central controller for the plant network.

A monolithic simulation model implemented in one simulation software system would be one option for implementing the plant network and the behaviour of all IT components. But there are several disadvantages or trade-offs that come with this solution as stated in [7]. First, there is a need to find a development environment that covers all used domains. Second, experts for each sub-system or domain need to work strongly together and have to use the same implementation environment to build the system simulation model. Third, models of the different storage and conversion technologies, or the implementations of the IT control logic cannot be easily reused in other application settings. Finally, the performance of the whole model, and therefore the scalability of the system model is limited by the execution environment of this single simulator. This is why the usage of an alternative implementation approach e.g. using a co-simulation framework is crucial. In our implementation of the system model, each component is modeled separately as a stand-alone black-box component which can be executed independently from each other in their own execution environment.

The physical plant models describing the conversion and storage functionalities represent the coefficients of the coupling matrix C and S in eq. (1) and (5), and are modeled as causal Modelica entities using the software Dymola. The input/output energy flows of the physical components according to the formulas are defined by input/output parameters of the respective component model and are mathematically equivalent to rows of the input and output vectors in the matrix equations. Each model has settable configuration parameters, which e.g. define operational and nameplate properties of the modelled plant, such as the maximum output capacity or storage volume within model defined limits. Control settings as dynamic input parameters of physical models allow to change the internal behaviour of the model (e.g. changing the storage or conversion rate). This allows the scaling of the model components according to a defined system model scenario and to influence their behaviour via the IT controller components. For usage by the system model, the Modelica components are exported as Functional Mock-up Units (FMUs), which are then executed as slave models in the chosen co-simulation framework [1]. The models of the IT components are implemented in Python. An application programming interface to STANET, a commonly used software to model i.e. natural gas and district heating infrastructures, allows for future integration of infrastructure models.

To implement a given system scenario, a choice of these component models have to be plugged together using the chosen co-simulation framework. For e.g. performing a step wise simulation which drives the simulation through the scenario additional functional components of the co-simulation framework are needed, where one acts as a scheduler driving the step-wise execution of the slave simulations and IT components forward, and a data synchronization component which waits for the outputs of the slave simulators and notifies the scheduler that a step has ended. The scheduler then distributes scenario data and other inputs to the slave and demand them to perform a step.

Figure 2 demonstrates the use of PROOF to implement the EHG system model. The graphics in the figure visualizes the used components as boxes and their interconnections as lines. The type of the different components are distinguished in the graphical model by different colored icons of the boxes (blue symbols mark physical component models, green IT components of the model, and grey symbols components organizing the step wise simulation). The scheduler component in the middle of the workflow initiates simulation steps by sending scenario and other input data for this step to all participating slave models / components and waits then until the synchronization component has collected output from each physical model. In each step, the EMS IT component with the dark blue symbol first determines if it should send new resource scheduling plans to the IT controllers of the technical plants, which in response dynamically send new control settings to the physical models. Then the physical models perform their calculations according to the given scenario input (e.g. weather), the defined control settings and other available input data, and send their results to the synchronization component, which gives feedback to the scheduler that all calculations have performed. Then the scheduler triggers the next step, until all steps have been performed. Underneath, the co-simulation framework collects all needed data for later analysis of the co-simulation run.

The modular approach discussed in this section allows it to adjust the EHG system model to many different scenarios under investigation without the need to modify the component models. Using other forms of components, the system model can e.g. be extended by an inverter and/or transformer component which connects the hub to an electrical grid using a solid state transformer and/or AC/DC inverter in a very modular and easy way. The decoupling between IT controllers and physical model components offers a flexible independent implementation of controller code in programming languages like Python while the physical models could be implemented using a dedicated physical modelling environment.

4 COMPONENT MODELS

To further illustrate this approach, a more detailed look at one of the component models will be presented in this section. As mentioned before, the EHG is a system network of various technical plants in different physical domains as well as Information and Communication Technology (ICT) components. In a general perspective each of those components can be seen as a separate simulation model, that need to have a well defined interface for using it in a general system model. To enable fast and simple composition of the general system model, the system interfaces of the component models need to be described in a formal way as an extrinsic interface, which can be instrumented by the co-simulation framework. As already described before, on the one hand this interface is defined by input and output parameters defining the energy flow connecting the physical components. These present single rows of the vectors L and P or M and E in eq. 1 or 5. On the other hand there are control settings as input parameters which allow to control the behaviour of the component model by the controller. Thirdly, configuration parameters can be set before the system simulation starts to configure the component model e.g. to have a certain storage capacity or output power. As one example from our use case, the extrinsic interface of the electrolysis is described with its input, output and configuration parameters in Table 1. Parameters can be divided into static and dynamic ones. While static parameters describe nominal values (e.g. so called nameplate and operational properties of a technical component), dynamic parameters indicate operational behaviour of the model. By using static parameters, the time to startup the plant ($t_{startup}$) as well as the minimum and maximum power input (P_{min}

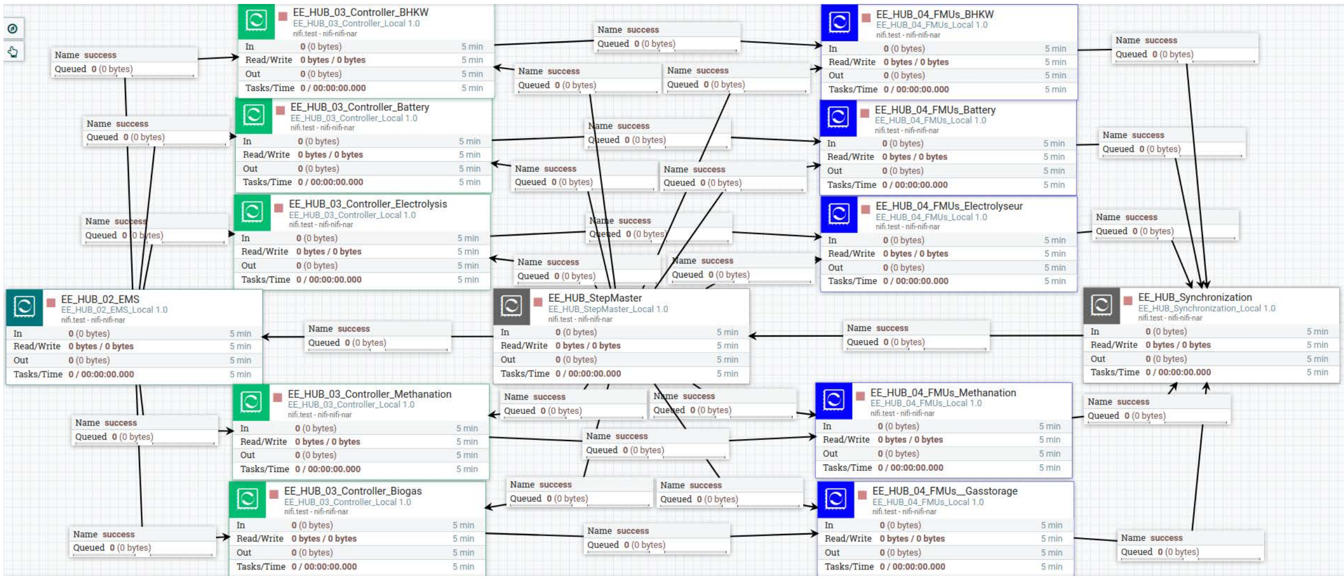

Figure 2: Graphical co-simulation model of the EHG on PROcess Operation Framework (PROOF)

Table 1: Parameters of the electrolysis Model

static Input Parameters		
Parameter	Description	Value
$t_{startup}$	derivative time constant	60 s
P_{max}	nominal power input	10^6 W
P_{min}	minimal power input	0.31×10^6 W
η	efficiency coefficient	0.73
$H_{S,H2}$	calorific value H_2	141.8×10^6 J kg^{-1}
dynamic Input Parameters		Unit
P_{set}	set point electric input	W
P_{last}	last electric partial load	W
dynamic Output Parameters		Unit
$\dot{m}_{H2}$	mass flow H_2	kg s^{-1}
P	current electric power	W

and P_{max}) are defined. Furthermore, the efficiency coefficient η for the conversion of electric power into H_2 and the calorific value of H_2 ($H_{S,H2}$) are stated. As dynamic input parameters, the model receives a set point as control value (P_{set}) from the IT controller for the consumption of electric power to convert into H_2 and the last (measured) value of its electrical load (P_{last}). This value guarantees that the model starts up with the value from last calculation step. As dynamic outputs, the model provides the mass flow of H_2 ($\dot{m}_{H2}$) and the effective consumed electric power P. As a convention every dynamic parameter is negative if it is consumed and positive if it is generated.

5 RESULTS AND DISCUSSION

For the evaluation of the feasibility of the implementation approach, the Energy Hub Gas (EHG) is implemented in a first step as a combination of Functional Mock-up Units (FMUs) and Python models as discussed above. According to figure 3, besides local renewable energy sources (RES), electrical and gas demand, generation is simulated by a combined heat and power plant (CHP). Furthermore, the EHG system network consists of an electrolysis plant with connected methanation as well as a bio-gas plant and storage units for electrical energy and methane depicted in figure 3. Two system

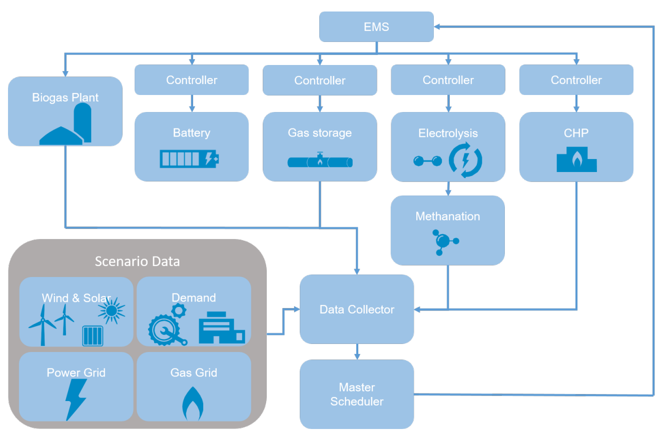

Figure 3: Implemented experimental setup of the EHG for both frameworks

models are implemented as co-simulation using a step-wise master slave approach: one by Mosaik framework and one by PROcess Operation Framework (PROOF) for evaluating the basic concept as described before. As can be verified both implementations delivering the same results. A central master scheduler coordinates the step-wise simulation by triggering the component models to deliver the results of the next simulation step. As scenario data weather data from the EHG location in Karlsruhe, Germany, for a typical meteorological year (TMY) is used as input for the generation of

RES namely wind and photovoltaic (PV) farms. Also, demand from regional industry in form of time series are taken into account. To investigate the possible impact of the EHG on the local power grid, a control strategy using an evolutionary algorithm is implemented as follows: While RES generate surplus energy, the EHG, depending on the objective functions, should consume this energy by either storing it into its storage units, or converting and deliver it to the gas infrastructure. If there is a lack of electrical power, the EHG should cover this by either reducing its consumption, discharging its storage or generating electrical power by the CHP. To face the dimension challenge, the electric power flow for the control strategy is based on real data exemplary set to -5.5×10^6 W. Therefore, the Energy Management System (EMS) controls the EHG components to try to generate a constant load of -5.5×10^6 W at the electrical connection point (ECP).

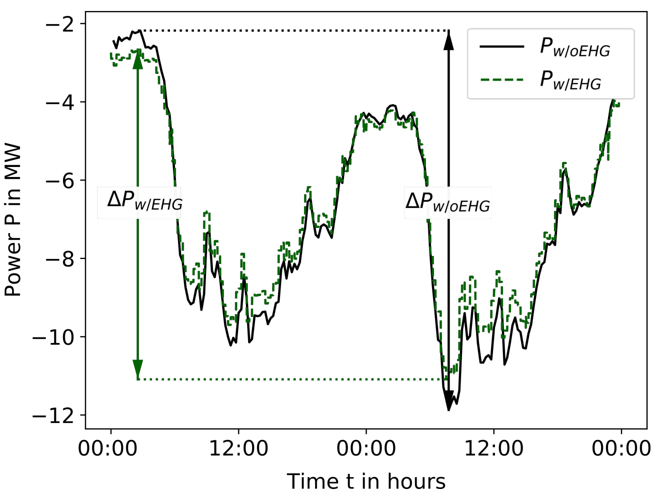

Figure 4: Resulting power w/ and w/o EHG obtained by Mosaik and PROOF

$$\frac{\Delta P_{w/EH} - \Delta P_{w/oEH}}{\Delta P_{w/oEH}} = \%\, P_{deviation} \tag{7}$$

$$\frac{E_{ex,w/EH} - E_{ex,w/oEH}}{E_{ex,w/oEH}} = \%\, E_{deviation} \tag{8}$$

In figure 4, the power flow at the ECP of the Energy Hub (EH) is outlined. For the evaluation of the simulation results, we choose a period of two days that are exemplary. The simulation calculates data for every 60 seconds. The EMS receives a control signal for the aggregated electric power of the EHG at its ECP depending on the basis of the estimated generation of RES and the demand. Thus, we consider the EHG as an ancillary service asset for the electricity grid, that connects the electricity grid with the gas grid; the control signal depends only on the estimated power flow in the electric grid. As an evaluation criteria, the power flow reduction on a percentage basis is calculated according to eq. (7) for two cases: with ($\Delta P_{w/EH}$) and without ($\Delta P_{w/oEH}$) the EHG interacting. It can be observed that the EH is able to reduce the effective power flow by 13.1%. According to eq. (8), the total energy exchanged at the ECP $E_{ex,w/EH}$ and $E_{ex,w/oEH}$ is an indicator for the possible effect an EHG can generate. For the considered time period a reduction of 3.5% is observed.

6 CONCLUSION AND OUTLOOK

The presented work shows the methodological setup and implementation of a cyber physical energy system (CPES) that (a) is independent of the used co-simulation framework, (b) offers ancillary services to the power grid, (c) supports local integration of renewable energy sources (RES) feed-in (electrons), and (d) serves as a regional gateway for renewable energy carriers (molecules). Scalibility and modularity are key characteristics for future expansion of the model to further investigate the Energy Hub Gas (EHG) approach in different scenarios and infrastructures. By varying the considered technologies (modularity) and certain plant sizes either by scale-up (scalibility) or numbering-up (modularity) the effects of different system network configurations on the power grid can be evaluated. The results of first simulations demonstrate the positive effect that an EHG can achieve by increasing the integration of local RES for relieving the power grid at the same time. For future research, enhancements of the EHG and the Energy Management System (EMS) are crucial for investigating more intelligent operation strategies to combine micro- and macro-economic aspects for specific setups. In addition, further ancillary services need to be implemented, e.g. grid code functionalities, to widen the possible application area of an EHG. Furthermore, a comprehensive analysis of forecast approaches for e.g. local RES generation need to be undertaken to get close to real world applications.

ACKNOWLEDGMENTS

The authors gratefully acknowledge funding by the German Federal Ministry of Education and Research (BMBF) within the Kopernikus Project ENSURE 'New ENergy grid StructURes for the German Energiewende'.

REFERENCES

[1] Torsten Blochwitz, Martin Otter, Martin Arnold, Constanze Bausch, Christoph Clauß, Hilding Elmqvist, Andreas Junghanns, Jakob Mauss, Manuel Monteiro, Thomas Neidhold, Dietmar Neumerkel, Hans Olsson, Jörg-Volker Peetz, and Susann Wolf. 2011. The Functional Mockup Interface for Tool independent Exchange of Simulation Models. *Proceedings of the 8th International Modelica Conference*, 105–114. https://doi.org/10.3384/ecp11063105

[2] Martin Geidel. 2007. Integrated Modeling and Optimization of Multi-Carrier Energy Systems. *ETH Zürich* (2007). https://doi.org/10.3929/ethz-a-005377890

[3] M. Geidl, G. Koeppel, P. Favre-Perrod, B. Klockl, G. Andersson, and K. Frohlich. 2007. Energy hubs for the future. *IEEE Power and Energy Magazine* 5, 1 (2007), 24–30. https://doi.org/10.1109/MPAE.2007.264850

[4] Jianlei Liu, Eric Braun, Clemens Düpmeier, Patrick Kuckertz, D. Severin Ryberg, Martin Robinius, Detlef Stolten, and Veit Hagenmeyer. 2019. Architectural Concept and Evaluation of a Framework for the Efficient Automation of Computational Scientific Workflows: An Energy Systems Analysis Example. *Applied Sciences* 9, 4 (2019). https://doi.org/10.3390/app9040728

[5] Jianlei Liu, Clemens Düpmeier, and Veit Hagenmeyer. 29-30 November 2017. A New Concept of a Generic Co-Simulation Platform for Energy Systems Modeling. In *FTC 2017 - Future Technologies Conference 2017*. 97–103. https://doi.org/Downloads/FTC2017/Proceedings/11_Paper_211-A_New_Concept_of_a_Generic_Co-Simulation.pdf

[6] Mohammad Mohammadi, Younes Noorollahi, Behnam Mohammadi-ivatloo, and Hossein Yousefi. 2017. Energy hub: From a model to a concept – A review. *Renewable and Sustainable Energy Reviews* 80 (2017), 1512–1527. https://doi.org/10.1016/j.rser.2017.07.030

[7] P. Palensky, A. A. Van Der Meer, C. D. Lopez, A. Joseph, and K. Pan. 2017. Cosimulation of Intelligent Power Systems: Fundamentals, Software Architecture, Numerics, and Coupling. *IEEE Industrial Electronics Magazine* 11, 1 (2017), 34–50. https://doi.org/10.1109/MIE.2016.2639825

[8] J. Ruf, M. Zimmerlin, P. S. Sauter, W. Köppel, M. R. Suriyah, M. Kluwe, S. Hohmann, T. Leibfried, and T. Kolb. 2018. Simulation Framework for Multi-Carrier Energy Systems with Power-to-Gas and Combined Heat and Power. In *2018 53rd International Universities Power Engineering Conference (UPEC)*. 1–6. https://doi.org/10.1109/UPEC.2018.8542066

[9] S. Schütte, S. Scherfke, and M. Tröschel. 2011. Mosaik: A framework for modular simulation of active components in Smart Grids. In *2011 IEEE First International Workshop on Smart Grid Modeling and Simulation (SGMS)*. 55–60. https://doi.org/10.1109/SGMS.2011.6089027

[10] Cornelius Steinbrink, Marita Blank-Babazadeh, André El-Ama, Stefanie Holly, Bengt Lüers, Marvin Nebel-Wenner, Rebeca P. Ramírez Acosta, Thomas Raub, Jan Sören Schwarz, Sanja Stark, Astrid Nieße, and Sebastian Lehnhoff. 2019. CPES Testing with mosaik: Co-Simulation Planning, Execution and Analysis. *Applied Sciences* 9, 5 (2019). https://doi.org/10.3390/app9050923

[11] Shalika Walker, Timilehin Labeodan, Wim Maassen, and Wim Zeiler. 2017. A review study of the current research on energy hub for energy positive neighborhoods. *Energy Procedia* 122 (2017), 727 – 732. https://doi.org/10.1016/j.egypro.2017.07.387 CISBAT 2017 International ConferenceFuture Buildings & Districts – Energy Efficiency from Nano to Urban Scale.