Energy Hub Gas: A Modular Setup for the Evaluation of Local Flexibility and Renewable Energy Carriers Provision

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Abstract—The ambitious targets for the reduction of greenhouse gas (GHG) emissions force the enhanced integration and installation of Renewable Energy Sources (RESs). Furthermore, the increased reliance of multiple sectors on electrical energy additionally challenges the electricity grid with high volatility from the demand side. In order to keep the transmission system operation stable and secure, the present approach adds local flexibility into the distribution system using the modular Energy Hub Gas (EHG) concept. For this concept, two different test cases are configured and evaluated. The two configured EHGs demonstrate the ability to provide flexibility and adaptability by reducing the difference between maximal and minimal load in the surrounding grid infrastructure by 30% in certain time periods. Furthermore, the average energy exchange is reduced by 8%. Therefore, by relieving the grid infrastructure in the local surrounding, the additional potential of RES is enabled and curtailment of existing ones can be reduced.

Index Terms—hybrid modeling and simulation, co-simulation, multi-domain systems, cyber-physical energy systems, energy hub

I. INTRODUCTION

More ambitious targets to cut carbon emissions - e.g. by at least 65 % by 2030 in Germany - drastically increase the need for integration and installation of Renewable Energy Sources (RESs). Given current geopolitics regarding European energy supply a fully renewable electricity supply is assumed to be required by 2030. The ongoing transition from conventional generator plants towards renewable, decentralized generation by Distributed Energy Resources (DERs) with volatile feed-in raises the challenge of a secure and stable power supply. Furthermore, the fuel-shift in different sectors, such as mobility and space heating, from liquid and gaseous energy carriers to electrical energy, increases the volatility on the demand side. Thus, supply and demand both challenge the existing electricity grid and its established structure. As a result, the traditional downstream power flow from feed-in on the $380\,\text{kV}$ grid level to consumption on a low voltage level is no longer a one-way grid. In this context, system operators on all voltage levels need to ensure a reliable and continuous

power supply for customers, which is even more difficult with the transition from a uni-directional to a bi-directional grid.

To this means, the Energy Hub Gas (EHG) concept depicted in Figure 1 combining different energy generation, storage and conversion technologies into one integrated plant network provides a promising approach to cope with several of these upcoming challenges. A wide range of technologies can be integrated into this system approach. This effective and smart interconnection between energy supply and demand infrastructures allows increasing local flexibility for electricity grid operation and the provision of renewable energy carriers. The decentralized approach can help accelerate the energy transition by reducing the required electricity grid extension by lowering the interconnection power flow between different voltage levels. Furthermore, local balancing ensures damping of power fluctuation in the immediate network environment and therefore acts as preventive congestion management. The attenuating effect an EHG can provide to the local surrounding grid infrastructure by its flexibility leads to the opportunity for further installation of RES. Hence, the established grid infrastructure can be relieved from additional integrated renewable generation. Different time constants between electricity and gas supply infrastructures are becoming useful by interconnecting these sectors through conversion and storage units. Gas infrastructure, storage units, and energy carriers are used to (a) reduce the operation cost for congestion management and re-dispatch while (b) gradually defossilizing non-electricity demand sectors. To evaluate the approach a flexible system simulation framework, as discussed in this paper, is necessary which allows for the evaluation of a wide range of specific EHG configurations and their corresponding use cases.

The usefulness of the modular EHG concept is evaluated for different scenarios and different periods of time. The investigated scenarios reflect a representative region with high solar power penetration as dominating renewable electricity
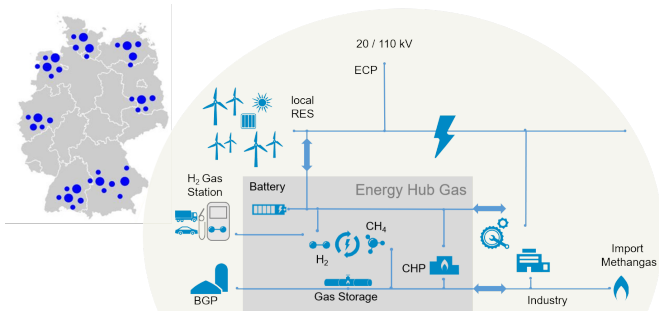
Fig. 1. Energy Hub Gas system overview

feed-in ("German South-West"), and a coastal region with typical high wind power penetration ("German North-West"). These renewable production scenarios are then combined with different demand characteristics. The overall objective is a significant and cost-effective integration of renewable generated power and provision of renewable energy carriers for hard-to-abate and hard-to-electrify demand sectors. The unique feature of the approach is the combination of these two objectives with an aggregation of today available technologies in a modular fashion and little infrastructure adjustments.

The present paper is organized as follows: Section II provides an overview of existing work in the context of Energy Hubs (EHs) and their applications. Furthermore, a distinction between the work presented here is given. In Section III, the mathematical basis of the EH concept is summarized. Next, the simulation setup with its framework character is presented in Section IV. A detailed look into the component models used and the test cases investigated is given. Following Section V, exemplary simulation results of two different test cases are evaluated and discussed. Finally, the paper concludes with Section VI and provides an outlook for future research.

II. RELATED WORK

As further development of the approach in [1], the Energy Hub Gas (EHG) concept utilizes a distributed system simulation model of a controllable modular set of technical plants. This system model interconnects electricity and gas supply with different final energy demand sectors (electricity, heat, fuel for mobility, chemical intermediate or commodity for industry) in a smart and flexible way, providing, e.g. utilities flexibility for grid operation. The present paper focuses on the modular design of the energy hub concept inspired by [2], [3] and [4], which allows adapting (the model of) the plant ecosystem to different settings of existing infrastructure and specific operational requirements. In addition to the physical interconnections of facilities presented in [1], this novel setup revises especially renewable gas components by deepening the level of detail for the conversion from electricity to both hydrogen and methane. As requested in [5] and [6], besides the main functionalities, the presented work considers local, sustainable mobility as fuel station hydrogen demand and connects to new hydrogen pipeline infrastructure, resulting in a more diverse and realistic scenario. In contrast to [7], [8] and

[9], for both gaseous energy carriers, feed-in pathways are also considered and made economically feasible by introducing a compulsory green gas quota for gas suppliers [10]. The EHG participates in fulfilling this quota together with large-central upstream renewable gas feed-in and existing distributed biomethane feed-in. The controversial topics of green gas certification and "colors" for different hydrogen origins are thereby not considered and discussed as constraints. For the present work, climate-neutral gas shall be considered of non-fossil origin. The positive correlation between low electricity prices, high renewable electricity feed-in and high need for congestion management leads to hydrogen production with decreasing carbon footprint. Local heat demand is modelled to provide a more complete analysis of simulation data, especially regarding the level of integration and economic cost for flexibility. The semantic description of the system and component behaviour and its extrinsic controllable interface is based on the hierarchical concept of Distributed Energy Resource (DER) modelling according to the IEC61850 standardization, especially part 7-420 with a focus on Managed Distributed Energy Resources (MDERs) [11]. The central control logic for steering the internal plant network and allowing control e.g. by utilities is provided by an Energy Management System (EMS) utilizing this semantic model internally. It provides a lightweight communication interface where external control can be provided by implementing grid code behaviour in a modular fashion. The EMS covers the possible complexity of the investigated EHG instance by defining a modular plugin interface for integrating the control interfaces of, e.g. technical plants or components. It aggregates their abilities in a black-box fashion to a composed mixed DER which is externally controllable. The provided control functionality for either transmission system operators (TSOs) or distribution system operators (DSOs) especially allows executing unit commitment schedules on a DER that can address re-dispatch 2.0 requirements for balancing generation and load or retrieving individual forecasting schedules of plants over $100\,\mathrm{kW}$ for planning. Internally, the EMS uses, in contrast to [12] a multi-objective optimization method [13] which converts the overall plant network schedule into an optimized set of schedules for each plant of the hub ecosystem.

III. THE ENERGY HUB APPROACH

The energy hub concept is a promising approach as a resource to increase flexibility for the electric grid to balance local generation and demand. In particular, Renewable Energy Source (RES) can be integrated by converting and storing different forms and carriers of energy in decentralized plant networks, as outlined in [5]. Furthermore, in [14] an application of the Energy Hub (EH) concept on a scale of a city district is proposed, which is suitable as one possible use case for the present concept. However, the present modular approach of the Energy Hub Gas (EHG) is designed to be used in a wide range of applications, from city districts to interconnection stations for the transmission grid. Within the concept of an EH, first introduced by [4] and [3], multiple

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energy conversion and storage units are grouped to condition, convert, and store various forms of energy and energy carriers. From a more abstract perspective, they build a black box with inputs and outputs of different energy types, which are internally converted between the different types or carriers. In addition, the input energy forms can be stored. Mathematically, the conversion process can be described as a coefficient matrix H_{ab} that connects multiple energy inputs I_ω to a number of energy outputs O_σ. A general conversion formulation with multiple inputs and outputs for a single unit consists of three parts: the power output vector L, the conversion coupling matrix C, and the power input vector P. Both P and L include all considered energy carriers or energy forms $[\alpha, \beta, ..., \omega]$ 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 relationships can be generically formulated as:

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

The components $c_{\alpha\beta}$ of the coupling matrix C are defined as coupling coefficients and map input to output power. $c_{\alpha\beta}$ can either convert between different energy carriers in the case of $\alpha \neq \beta$, or pass through an energy carrier if $\alpha = \beta$. In both cases, $c_{\alpha\beta}$ can be between 0 and 1, or equal to 1. If $c_{\alpha\beta}$ is equal to 0, it represents no coupling between given energy carriers. The different kinds of conversion are summarized in Table I.

C may depend on the power input or other parameters, e.g. a target value as a control signal received from an Energy Management System (EMS) on a conversion unit, therefore $C = f(P, t, ...)$, which leads in general to non-linearity for C. Another important property of eq. (1) is that it represents an under-determined system of equations if more than two energy carriers are considered. This leads to the fact that C is not invertible. Thus, there is no unambiguous solution, and it is possible to optimize the coupling matrix.

TABLE I
CONVERSION TYPES [3]

Type of coupling	Coupling factor	Energy carriers
Lossless transmission	$c_{\alpha\beta} = 1$	$\alpha = \beta$
Lossy transmission	$0 < c_{\alpha\beta} < 1$	$\alpha = \beta$
Lossless conversion	$c_{\alpha\beta} = 1$	$\alpha \neq \beta$
Lossy conversion	$0 < c_{\alpha\beta} < 1$	$\alpha \neq \beta$
No coupling	$c_{\alpha\beta} = 0$	any α, β

Two important characteristics of the converter coupling matrix are stated in [3] and can be summarized as

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

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

The desired EH concept includes also storing of energy over a certain time, which needs special consideration in comparison to the conversion process and leads to a time dependency of all modeling variables. In [3], the influence of a storage on the total power output is summarized in the storage flow vector

$$M^{eq} = CQ + M. \quad (3)$$

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

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

with e_α and e_β the charging and discharging efficiencies for the respective energy carriers. $\dot{E}$ represents the change in stored energy.

Combining the formulation for energy storage with the general formulation for an energy hub results in the dynamic system equation in matrix notation

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

The complete EHs output power is represented as:

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

IV. SIMULATION SETUP

As a generic setup, the concept and corresponding system simulation model separate control and communication logic from the physical models of the technical plants in a modular fashion. With this, different components of the Energy Hub Gas (EHG) system are represented either by Functional Mock-up Units (FMUs) or simulation models implemented in Python for generic control and communication behaviour. The presented implementation of revised models illustrates the advantages of this modular approach. Furthermore, added features pose new sets of boundary conditions to the system and provide an opportunity to display advantages of the modular approach in both simulation setup and Energy Management System (EMS). Finally, the modules are combined into a system model to set up a specific application environment using a distributed simulation runtime environment, which allows executing the model to perform different test cases for evaluation. The general data flow of the simulation system follows the concept depicted in Figure 2. Blue arrows indicate direct data transmission within the same time step, whereas
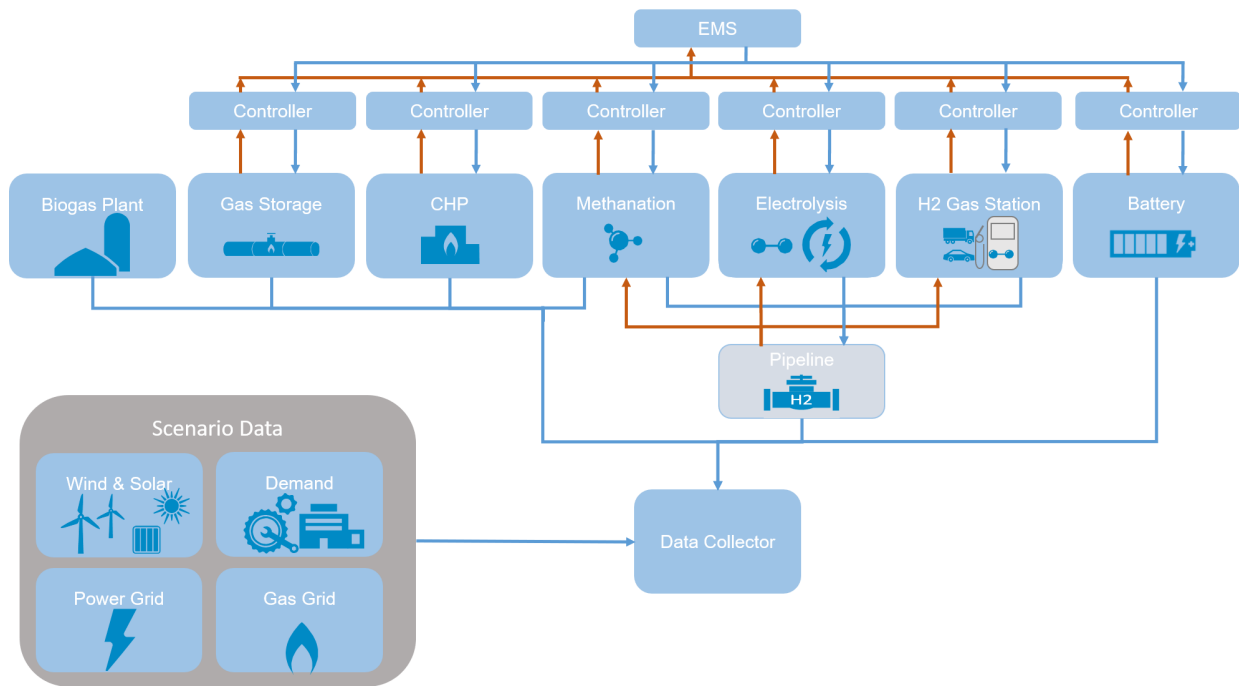
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Fig. 2. Energy Hub Gas simulation setup

red arrows indicate an asynchronous connection, where data is transmitted in the following time step. The EMS calculates schedules for all six facilities in this example and sends them to the respective controller instances. Each controller processes these schedules to a time series of single setpoint commands forwarded to the facility. A facility tries to follow these setpoints in compliance with its physical boundaries, resulting in a realistic behavioral trace of each facility. Outputs of the facilities are routed into the Data Collector, where they are finally processed and stored. Both scenario data and biogas plant produce behavioral traces without controllers as they only react to the current simulation time. Finally, the behavior of the hydrogen pipeline, which is added to the system and bidirectionally coupled with methanation, electrolysis and H_2 gas station, has to be taken into account. The pipelines ensure energy conservation in the simulation system as methanation and gas station cannot consume hydrogen when the pressure of the pipeline falls under a threshold, respectively the electrolysis stops production when a pressure limit is surpassed.

The modular, scalable, and extendable setup allows to re-use, add and parameterize individual component models within a system model and therefore, to easily create dedicated instances of the EHG for different application settings. This facilitates the configuration, evaluation, and usage of a specific EHG instance in different application environments and use cases.

A. Component Models

The simulation setup contains component models for a polymer electrolyte membrane electrolysis (PEM), a three-phase methanation (3PM), a combined heat and power plant

(CHP), a lithium-ion battery and a hydrogen supply unit for a hydrogen fuel station based on FMUs. The FMUs are created in Dymola using Modelica. Furthermore, a methane storage implemented in Python is included. The models are based on technical parameters, e.g. nominal power. These parameters are provided in Table II. Detailed electrochemical and thermodynamic processes are not part of the component models. Specific communication interfaces allow for communication in order to receive schedules from the EMS and to send relevant operating status to the Data Collector.

The sector coupling models CHP, PEM, and 3PM instrument key parameters for modeling conversion efficiency, systems dynamics, as well as minimum and maximum power. The conversion efficiency of the electrolysis is the ratio between specific power demand and corresponding hydrogen production [15]. The 3PM is assumed to convert hydrogen and carbon dioxide at the stoichiometric ratio of the methanation reaction [16]. The electrical efficiency of the CHP is taken from [17]. The system dynamics of CHP, PEM, and 3PM are modeled using characteristic start-up times from stand-by to full load. Information about the load status of the assets are sent to the Data Collector. The lithium-ion battery and the methane gas storage are modeled using parameters for capacity and maximum rate of charging and discharging [18]. Information about the current state-of-charge (SOC) is sent to the EMS as model output. The hydrogen supply unit is a gas buffer tank, which has to be completely loaded at certain times in order to be delivered to a gas fuel station. Charging times of the supply unit are scheduled by the EMS.

Parameter	Value
CHP	
maximum power output	2 MW
minimal power output	0.7 MW
electrical efficiency	0.43
start-up time	120 s
PEM	
maximum power input	1 MW
minimal power input	0.31 MW
efficiency coefficient	0.73
start-up time	60 s
3PM	
maximum production rate	$65\,\mathrm{kg\,h^{-1}}$
minimum production rate	$10\,\mathrm{kg\,h^{-1}}$
specific hydrogen demand	$4\,\mathrm{mol\,mol^{-1}}$
start-up time	60 s
Battery	
capacity	3 MW h
maximum charge power	1 MW
maximum discharge	1 MW
charging efficiency	0.92
discharging efficiency	0.92
Methane storage	
capacity	1500 kg
maximum charge power	$0.27\,\mathrm{kg\,s^{-1}}$
maximum discharge	$0.27\,\mathrm{kg\,s^{-1}}$
Hydrogen fuel station supply	
maximum charge rate	$1.8\,\mathrm{kg\,h^{-1}}$
time period of H_2 delivery	168 h

B. Test Case Description

In order to use the framework described in the previous section to answer research questions, a methodical preparation of test and evaluation data for driving the simulation through use case scenarios related to research questions is required. In [19] a systematical assessment methodology is proposed that is suitable for the presented EHG approach due to its holistic scope of the used energy carriers. A test environment emerges as an instance of the framework by combining the specification of individual models, the scenario data, and previously determined evaluation criteria. Within this test environment, raw data are generated as results to which the evaluation criteria are applied. This results in the answers to the previously posed research question and goal settings. The separation of the individual data, models, and the framework has the advantage of flexible adaptation to a wide variety of use cases while at the same time allowing comparability. Thus, the results of one test environment can be compared with those of another. In [19] the test case description is divided into goal settings, operational strategy, system configuration, and scenario data.

As shown in Figure 3, the data needed for a complete simulation and evaluation circle can be matched to the basic idea of an EHG presented in the previous section. With the extracted information from the input data, for example, global radiation from weather data, the simulation system converts it within the coupling matrix C to information about the power generation by Renewable Energy Source (RES). The information delivered by the grid data is, for example the actual load without the EHG interacting. The control signal is the interface for external authority, e.g. distribution system operator (DSO) or transmission system operator (TSO), to make use of the offered flexibility from the EHG. In our example setting the control value is an active power signal for 15 minutes intervals according to the re-dispatch and day-ahead unit commitment measures. Furthermore, the scenario data include price information for the relevant energy carriers, for example, hydrogen, electricity, and natural gas. By extracting and directing the relevant information to the inputs of the EHG simulation model, respectively, the coupling matrix C from eq. 1, the raw data are delivered by the co-simulation system described in the previous section. Each component model calculates independent results that need to be collected and analyzed. These results are mapped onto the output vector L used to evaluate the results further.

C. Industrial Area Karlsruhe (Germany)

The first test case to investigate the presented system approach targets an industrial area in the south-west region of Germany which is a characteristic region for high Photovoltaic (PV) penetration. The considered time horizon reaches from January 2021 to September 2021. Furthermore, the installed power of Wind Power Plants (WPPs) is relatively low compared to the northern part of Germany, which is considered in the second test case. In industrial areas, the load curve is dominated by a workday pattern, and the dependence on the outside air temperature is smaller. This leads to the following comprehensive test case description:

Goal setting: Investigate how and to what extent the EHG system approach can help to reduce Renewable Energy (RE) curtailment because of feed-in management or congestion management. Thus, providing flexibility to attenuate grid variability is synonymous with integrating RES. Furthermore, the ability to provide and the amount of flexibility provided by the instantiated system model is of high interest. Thus, a direct connection can be drawn to the possible substitution of fossil chemical basic molecules, e.g., methane.

Operational strategy: The operating strategy of the presented experimental setup aims to implement grid-serving control of the EHG with simultaneous cost-optimized use of its internal plants. The internal system structure is represented in a more abstract way and thus hidden by the EMS. Therefore, a schedule for the following 24 hours can be transmitted to the entire energy hub, which is used to control the internal systems in an optimized way. In this way, the local curtailment of renewable energy feed-in will be reduced.

System configuration: The system configuration schema introduced in Figure 1 consists of the EHG system model including the presented component models. Furthermore, for modeling the surrounding system into which the EHG model configuration is integrated, local surrounding RES and their generation, local demand by industry and regional mobility demand are respected by the scenario data. For test case one
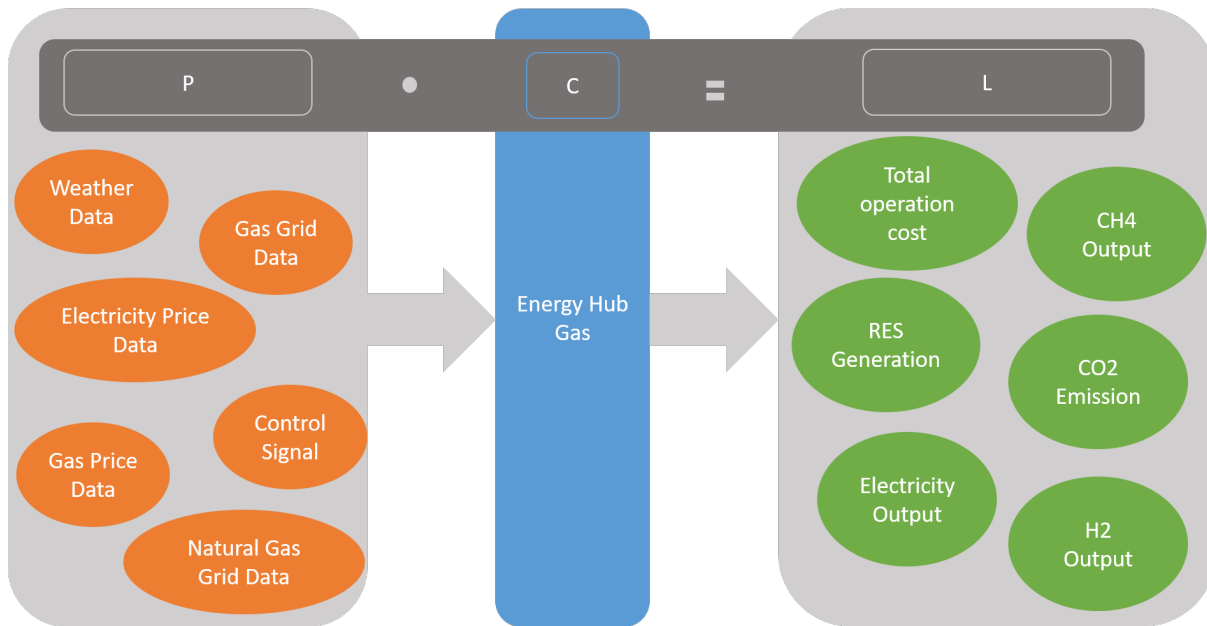
Fig. 3. Test case data within the Energy Hub Gas system

(TC1) the considered RES possess the following peak power: local PV plants with $10\,\mathrm{MW\,peak}$ and a single WPP with $2.5\,\mathrm{MW\,peak}$.

Scenario data: To complete the set of information for a simulation and evaluation run, scenario data are needed. Weather data regarding solar irradiance and wind speed are used to determine renewable generated energy. These are available for TC1 as real-world data from measurements at the Campus North of the Karlsruhe Institute of Technology (KIT). The price information for the period under consideration in 2021 has been prepared from publically available sources, e.g., Bundesnetzagentur — SMARD.de. The electricity prices are data from the EPEX SPOT day-ahead market. The prices for the other energy sources are average prices from 2021 and relate to the entire period under consideration, as these are not traded on an intra-day market. The control signal, which is taken into account in a real application through communication with a network operator and based on its forecast, is based on a measured load series. A perfect forecast of the grid situation for the next 24 hours is assumed in each case.

D. Industrial Area in northern Germany

The second test case is located in the northern part of Germany close to the coast. This area shows a high share of WPP generated RE in connection with low consumption. The amount of curtailed RE from WPP is of high interest for the operation of an EHG from an economic point of view, as well as for the society from an ecological point of view. Absolute reduction of electricity from RES under feed-in management in 2020 were $6146\,\mathrm{GW\,h}$, which is about 3% of the total generated RE [20]. The considered time horizon is the same as in TC1. This leads to the following test case description:

Goal settings: The avoidance of curtailment of RE is the primary goal since, on a coastal level, there is significantly more generation by WPP than consumption and thus the large transmission lines are to be relieved by transferring the RE to other sectors. At the same time, the provision of renewable chemical energy sources offers an opportunity to reduce greenhouse gas emissions in different application areas.

Operational strategy: The operating strategy of the experimental setup presented aims to implement grid-serving control as described in TC1. With adapted to external requests of utilities, internal generated and optimized schedules for the following 24 hours the EMS offers flexibility to the DSO or TSO to integrate the fluctuating generation by RES rather than curtailing them. The economic benefit of this operating strategy consists of two parts: First, selling the long-term storable energy carriers converted from RE is the main part. Second, the compensation payment the DSO or TSO must pay for curtailment under feed-in management to the RES operator leads to additional income.

System configuration: The system configuration for test case two (TC2) differs only in the considered RES to integrate. The EHG system model including the same component models with the same rated power as in TC1 are located next to a RES farm with a PV plant with $2.5\,\mathrm{MW\,peak}$ and WPPs summarized to $10\,\mathrm{MW\,peak}$. Furthermore, the local demand of industry and the regional mobility demands are identical to TC1.
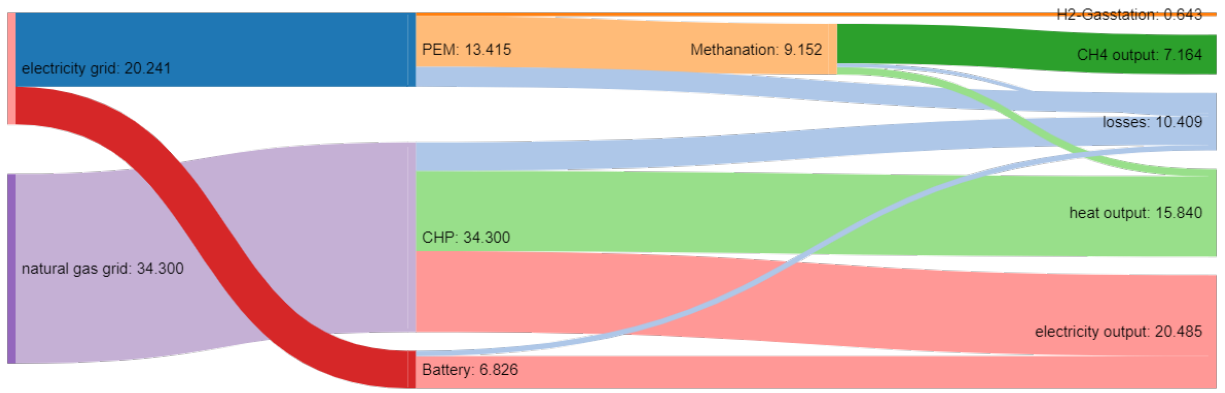
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Fig. 4. Energy flow chart for March 3rd, 2021

Scenario data: Weather data is taken from measurements of the Deutscher Wetterdienst (DWD) in a 10-minute resolution. The control signal is adapted by calculating the possible renewable generation for the considered area. Furthermore, the same data is used as price information as in TC1. In addition, the same load curve of local industry is used.

V. Evaluation

The usefulness of the modular Energy Hub Gas (EHG) concept is exemplarily evaluated for the two different test cases described in the previous section. Two sets of evaluation criteria are used for the evaluation of the EHG operation: (a) In order to assess the EHG's ability to deliver flexibility in different time scales, a power spectral density analysis is applied. Short-term (minutes to a few hours) and mid-term (hours to a few days) flexibility provisions can be individually weighted and attribute different economic values to different time scales. (b) Ecological (e.g. CO_2 reduction of provided final energy), economic (e.g. operational cost), and efficiency (e.g. conversion and storage energy losses) properties are assessed by either a Sankey-diagram or the analysis of exemplary load profiles. Furthermore, the attenuating effect of the EHG is evaluated by the reduction of the difference between the minimum and maximum active power load according to eq. (7) over one day. The reduction of exchanged energy in the considered grid segment is calculated to emphasize the potential nominal power for additional Renewable Energy Sources (RESs) that again would increase the volatility.

$$\frac{\Delta P_{w/EH} - \Delta P_{w/oEH}}{\Delta P_{w/oEH}} = \% \ P_{deviation} \qquad (7)$$

For the evaluation of the simulation results, exemplary days are considered on which the described operation of the EHG becomes particularly clear. In addition, the entire period is evaluated in order to illustrate the grid-serving operation of the decentralized plant network.
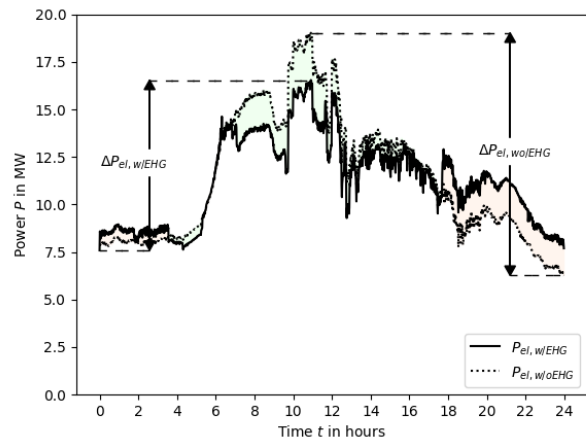

Fig. 5. Resulting power w/ and w/o EHG interacting at March 3rd, 2021

With test case one (TC1), the ability of the EHG to provide renewable chemical energy carriers to sectors where the processes are difficult or expensive to electrify is evaluated. The industrial area in TC1 described in the previous section with its demand for chemical energy carriers can be provided with the energy flows shown in Figure 4. Depicted are the energy flows, including the conversion paths of the individual energy sources as of March 3, 2021 including the total losses (10.4 MW h) due to conversion and storage efficiencies. It is depicted that around 20.2 MW h of electrical energy is converted to around 7.2 MW h methane, 0.6 MW h hydrogen for the gas station and 6.8 MW h are temporarily stored in the battery. By replacing about 7.2 MW h of natural gas with renewable methane, approximately 1.45 t of CO_2 emissions can be avoided. Most of the energy is already sourced from the natural gas grid and converted to electrical power and heat by the combined heat and power plant (CHP). However, the fluctuation in the electrical grid can be used to contribute other chemical energy carriers from renewable energy, for example, hydrogen. A total amount of 18.7 t of hydrogen is produced

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under the grid-supporting operation conditions over the entire simulation period of nine months. By selling this product as green hydrogen, ignoring possible uncertainties or cost-related to certification, a revenue of around $107\,000\,\text{EUR}$ can be achieved.

A more detailed look into the electrical energy amount depicted in Figure 4 is given in Figure 5. Here, the electrical load profile with and without the EHG interacting is shown. Negative values mean backfeeding into the transmission grid level. The attenuating potential of the EHG can be quantified for the considered date by a reduction of 29.8% concerning the maximum power deviation over one day according to eq. 7. This relieves the existing grid infrastructure and opens the possibility for additional RESs. If the entire simulation period (1st January until 30st September 2021) is considered, the average attenuation through the EHG is 11.6%.

A. Test Case Two

In test case two (TC2) the evaluation is focused on the possibility of relieving the grid infrastructure for increasing renewable feed-in. Therefore, an exemplary load curve from 25th of February, 2021, is evaluated and shown in Figure 6. The power flow within the considered grid segment is depicted with and without the EHG interacting. A reduction by 13.1% is achieved concerning the difference between maximum load and maximum feed-in.

Furthermore, the energy exchanged within the evaluated day at the electrical connection point (ECP) is abated by 30.2%. The colored areas in Figure 6 mark the positive (green) and negative (red) power adjustments achieved by the EHG interacting and resulting in a total reduction of $24.8\,\text{MW h}$ within one day. The red area in Figure 6 describes the additional load caused by the EHG to convert electrical power to hydrogen for either direct use or further processing within the methanation. The total additional load summarized over the evaluated day is $11.98\,\text{MW h}$. This reduction, in combination with the attenuated load curve, offers the opportunity to install
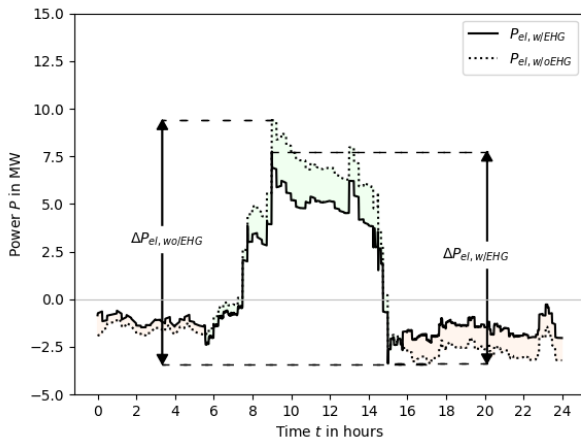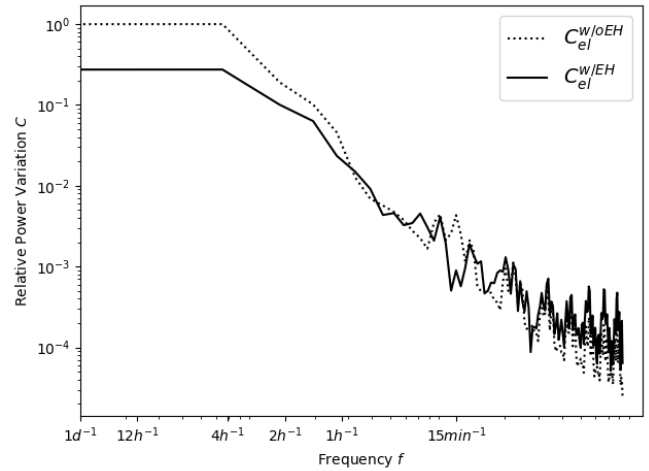

Fig. 7. Power Spectral Density of the EHG on February 25$^{\text{th}}$, 2021

additional RES or integrate existing but curtailed RES on the same scale without extending the grid infrastructure. Using the curtailed energy, there is a potential reduction in CO_2 emission of around $4.3\,\text{t}$ according to the emission coefficients ($360\,\text{g/kWh}$) given by [21]. Furthermore, the average compensation paid by utilities to RES operators for curtailment is $124\,\text{EUR/MWh}$ according to [20], which results in additional revenues of around $1485\,\text{EUR}$. At the same time, the amount of green hydrogen or methane provided by the EHG by using this energy results in additional income. The evaluation of the entire simulation period of nine months results in an average reduction of power fluctuation by 4.9%. Furthermore, the average energy exchanged at the ECP is reduced by 7.7% per day with a total production of $26.97\,\text{t}$ hydrogen. To assess the quality of the flexibility provision and hence the electricity grid supporting service the EHG can deliver, a Power Spectral Density (PSD) analysis is conducted. Figure 7 shows the relative power variation c with and without the EHG interacting over the frequency f for the evaluated day. The solid line depicts the power variation with the EHG trying to follow the schedule provided by the grid operator. For a frequency of $1h^{-1}$ or lower, the EHG can reduce the fluctuation, but within higher frequencies, there is no effect on the power variation. Although the EHG is equipped with components that can adjust their power in the frequency range of seconds, it is not possible to implement this to reduce the power variation.

VI. CONCLUSION AND OUTLOOK

In the present work, a multi-energy carrier co-simulation system is introduced as Energy Hub Gas (EHG), and the used modular component models are described. Based on the Energy Hub (EH) concept by [3], the modular and highly flexible system is built as an EHG. The usefulness of the approach is investigated in two test cases.

Results show that the bidirectional sector coupling of gas and electricity grid can provide flexibility to the power grid

Fig. 6. Resulting power w/ and w/o EHG interacting at February 25$^{\text{th}}$, 2021

so that volatility is reduced. By reducing the volatility, the EHG helps grid operators integrate higher shares of renewable generated power into their network with fewer infrastructure measures. This leads to a total reduction in CO_2 emissions and possible less grid extensions on a high voltage level. The modular concept evaluated in the presented work can deliver grid supporting services via local flexibility adjusted to the individual requirements of different use cases. By adapting parts of the system network of the EHG, a significant cost and time efficient increase in integrating Renewable Energy Sources (RESs) can be observed for the investigated scenarios and infrastructure.

Further research is necessary to investigate the dependencies between presented scenarios, test cases, and EHG instances. The contribution an EHG can make to securing gas supply in consideration of significantly rising prices is of further interest. The presented possible adaption of the system configuration can be used for a planning optimization to find an optimal component mixture within the EHG. Future work should also investigate different time scales and horizons for the optimization method to find schedules that better approximate the received control signal. To further improve the scheduling method by the Energy Management System (EMS), different optimization objectives should be included in future work to investigate the complete benefit an EHG can provide.

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