Investigation of Dynamic Interactions in Integrated Energy Systems

Jan-Peter Heckel, Anne Senkel, Carsten Bode, Oliver Schülting, Christian Becker, Gerhard Schmitz and Alfons Kather

***Abstract*— Integrated Energy Systems (IES) are assumed to be an appropriate concept to enable a 100 % renewable energy supply. In IES, the energy grids of the energy sectors electricity, gas and heat are connected by coupling technologies such as Power-to-Gas and Power-to-Heat. These physical and technical couplings can lead to intended and unintended interactions between the three subsystems. On the one hand, these interactions can provide supporting flexibility. On the other hand, these interactions can compromise the system stability. A future energy system must feature resilience, the ability to withstand and recover from disturbances, to enable the necessary security of supply. This paper presents a dynamic system model that is suitable to analyze the dynamic interactions of subsystems and to develop required resilience strategies. Furthermore, a Resilience Index concept is applied to quantify and evaluate system resilience. Given the dynamic simulation approach and the Resilience Index, a set of scenarios are analyzed, showing that dynamic interactions in IES with Power-to-Gas and Power-to-Heat have an influence on the frequency and voltage stability of the electric subsystem. This can affect the resilience positively as well as negatively. Consequently, modifications in the overall energy system must be investigated precisely and these modifications should focus on resilience based on redundancy.**

***Index Terms*— Integrated Energy System, Dynamic Simulation, Resilience, Stability, TransiEnt Library.**

I. Introduction

A. Motivation and Background

To fulfill the goals for the limitation of climate change, the share of renewable energies must be increased successively until the energy supply is based on 100 % renewables. Volatile generation and fluctuating energy demand must be balanced. Energy storage units will provide this capacity. Storage capacities in the electric power system are limited because, in contrast to heat or gas grids, the electric grid itself cannot be assumed as an energy storage. Furthermore, battery storage plants have high costs per unit of energy stored due to their technological complexity. Pumped storage plant installations are dependent on the geographical situation. In many countries, construction of additional pump storages is not feasible. Hence, coupling electricity, gas and heat systems should enable access to the storage capacities of the gas and heat sector. Gas and heat storage units have lower specific costs per energy quantity due to their simpler designs and the high specific energy capacities of their fluids [1,2]. Primary coupling technologies such as Power-to-Gas (with reconversion to electricity) and Power-to-Heat connect the subsystems of the energy sectors electricity, gas and heat in both directions. Thus, an integrated energy system (IES) is created. These energy systems are also referred to as Smart Energy Systems [3].

B. Relevant Research

In research, IES are widely analyzed using optimization models like in [4]. The review papers [5] and [6] show that optimization is widely used for the analysis of IES. In the literature review of [7], the authors' approach is mentioned as the only approach for the analysis of IES using dynamic simulation with a model library and the consideration of disturbances. With optimization models, it is possible to find suitable designs in terms of affordable economic costs or carbon dioxide emissions. In the regarded optimization models, the remaining important requirement of the security of supply in the IES is only considered in terms of the balance of active power in each optimized time instance. Like this, the security of supply is already part of the model and cannot be analyzed since the above condition cannot be violated. For the actual evaluation of the security of supply and thus resilience and stability in IES, other methods must be used. The method of choice is the dynamic simulation. Dynamic modelling and simulation for the assessment of the system and grid stability have been used for investigating within energy systems of only one energy sector in research for many years, e.g. for the electric grid [8]. The necessity of dynamic simulation of IES including all involved components becomes apparent when dynamic interactions between the three energy sectors in IES should be taken into account. These interactions can, on the one hand, improve the resilience of the IES by providing the

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necessary flexibility. On the other hand, the dynamic interactions can lead to system stability issues that must be avoided. In [9] a whole new approach for dynamic simulation is presented. It is based on a concept called Energy Network Theory and thus not comparable to the authors' approach in this paper. In [10], an approach for a dynamic simulation of IES is presented. This approach uses co-simulation and disturbance are not considered. The paper [11] presents a different dynamic simulation approach regarding different time scales. The presented approach does not feature the necessary modularity for representing different IES models on different spatial scales. A disturbance is investigated. However, the focus lies more on simulation errors and dynamic interactions are assessed neither in detail nor with a characteristic number.

C. Contribution and Organization

This paper presents a method and a model for the evaluation of dynamic interactions in Integrated Energy Systems in terms of resilience. Based on simulation results of the IES model, resilience in the context of dynamic interactions in IES is assessed quantitatively for the three sectors electricity, gas and heat. Thus, the necessity of applying multi-domain dynamic simulation based on ordinary differential equations for this purpose is demonstrated. The method enables evaluation of IES behavior in normal operation as well as during disturbances. Hence, realistic IES are implemented in the framework presented and assessed in terms of the security of operation and supply.

The second section describes and explains the methodology used for the analysis. Section III presents the simulation model with different scenarios and their simulation results. The fourth section contains the discussion of the results. The paper ends with a conclusion and an outlook to future research activities that will follow up on the findings in the context of resilient operation of IES.

II. Methodology

In this section, the methodology used to derive the results is presented and explained. First, the dynamic simulation approach is described. Afterwards, the system model is presented. For the quantitative evaluation of the simulated scenarios, the resilience index is introduced in the third part of this section.

A. Dynamic Simulation

For the analysis of dynamic interactions as well as the stability and resilience assessment, dynamic simulation is used as motivated in the introduction. All dynamic simulations in the underlying project "Resilience of integrated energy networks with a high share of renewable energies – ResiliEntEE" (funded by the Federal Ministry for Economic Affairs and Energy) are performed using the object-oriented Modelica description language [12]. It allows an equation-based and acausal modeling of components from the three sectors electricity, gas and heat in one system model. In the project ResiliEntEE, the freely available TransiEnt Library [13], containing such component models, is used. The TransiEnt Library was originally developed at the Hamburg University of Technology and has been widely extended and improved during the project ResiliEntEE [14], [15].

In the gas sector, the gas grid modeling has been enhanced by adding various simplifications that numerically improve models. Also, a physical pressure loss model was developed. This allows the dynamic modeling of spatially distributed national gas grids and their simulation in IES.

For the electrical sector, the modeling has been extended by a range of new component models based on a new electrical interface. The *ComplexPowerPort* allows the modeling of interconnected transmission and distribution grids in a unipolar representation by using the complex bus voltage as the modelling approach at the beginning of the project ResiliEntEE only allowed the consideration of electric grid as one busbar or copper plate respectively. As new components, models for steady state and root mean square (RMS) phasor-based simulation have been added. For the steady state component models, the load flow bus types and models for transmission lines and transformers are newly implemented within the TransiEnt Library. In the field of dynamic RMS simulation component models, new literature-based models for synchronous machines with automatic voltage regulators (AVR), excitation systems and over-excitation limiters (OEL) have been added and validated. Power plant models with controllers for power reserve allow the modeling of the frequency stability. Dynamic load models and a model for an on-load tap changer (OLTC) are given for the assessment of dynamic voltage stability. Additionally, the TransiEnt Library includes models for renewable energy generation plants such as wind power plants, photovoltaics plants and fuel cells [16], [17].

For the heat sector, a low-order approach is integrated in the modeling of the space heat demand. To maximize numeric efficiency, the separate heat capacities and conductors representing the buildings' components are aggregated [18]. Therefore, for the investigated housing area, heat gains and losses of one characteristic building are modelled based on the according physical relations. The connection between this building model and its heat supply is realized by a *HeatFlowMultiplier*, a model which scales up the computed heat demand according to the size of the considered housing area.

B. System Model Description

In the project ResiliEntEE [19], different demonstration models for IES have been created. For this paper, the focus is set on dynamic interactions between the sectors electricity, gas and heat. Fig. 1 shows an overview of this IES model. The simulations are performed using Dymola [20]. An electric grid model that is vulnerable in the context of voltage stability in the form of the N5area is chosen [21]. The N5area grid is a reduced-size model of the NORDIC32 Test System with five busses which can be used for voltage stability investigations. A biomass power plant, a combined heat and power plant (CHP plant) and a wind power plant park feed the grid. The biomass power plant and the wind power plant park are the renewable generation plants in the model. Each bus contains a dynamic load model [22] representing a high usage of electric heating. The revised Karlsson and Hill load model by Xu and Mansour is extended by a linear steady state frequency dependency,

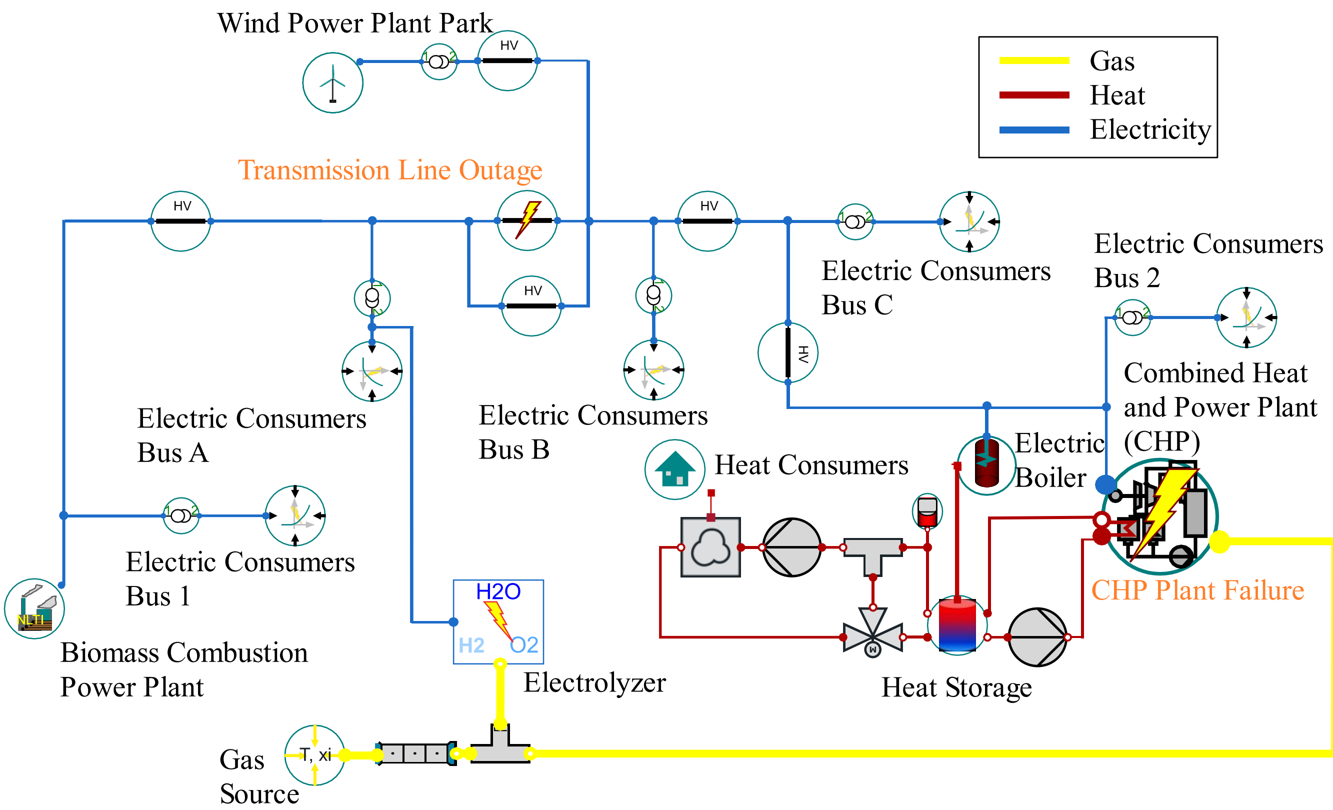

Fig. 1 Proposed test system model for IES.

which represents induction motors, and thus a frequency dependency of active and reactive power. The transformers are modeled as OLTC with a primary side nominal voltage of 380 kV and a secondary side nominal voltage of 110 kV. The N5area system shows voltage critical behavior in dependency of the load situation.

The gas system is reduced to an ideal gas source for natural gas, a gas pipe, which represents the gas grid, and a gas junction for connecting an electrolyzer and the CHP plant to the gas grid. The electrolyzer is connected to the electric grid Bus A. It is activated when the frequency in the electric grid exceeds 50 Hz, which can be considered a simplified control to provide negative balancing power. Because of the voltage critical behavior especially at grid Bus A, the electrolyzer is only active if the bus voltage is higher than 109 kV. The CHP plant is connected to the electric grid Bus 2.

The CHP plant supplies the heating network. For buffering the heat flow rate to the heat consumers, which are modelled as described in Subsection 2.1 of this section, a heat storage is used. The heat storage is modelled with finite volume discretization. For redundancy reasons, an electric boiler with the same thermal power as the CHP is added. Table I shows additional parameters of the overall IES model.

TABLE I
PARAMETERS OF THE ENERGY SYSTEM'S COMPONENTS

Parameter	Value and Unit
Gas Sector	
Feed-In Pressure at Gas Source	12.5 bar
Minimum Pressure CHP	1.2 bar
Length of the Pipelines	10 km
Volume of the Gas Grid	2113.5 m^3
Heat Sector	
Number of Households	20 032
Nominal Heat Flow Rate CHP	96 MW
Volume of Buffer Storage	5504 m^3
Supply Temperature	80 °C
Nominal Mass Flow Rate	1200 kg/s
Nominal Power Electric Boiler	96 MW
Efficiency Electric Boiler	0.95
Electric Sector	
Nominal Power Biomass Plant	3000 MW
Nominal Power Wind Farm	200 MW
Nominal Electric Power CHP	100 MW
Nominal Power Electrolyzer	100 MW
Power Factor of Loads	0.866 inductive
Frequency Dependency of Active Power	1.9 s
Frequency Dependency of Reactive Power	1.2 s
Nominal Active Power of Load 1	203 MW
Nominal Active Power of Load A	101.5 MW
Nominal Active Power of Load B	1522.5 MW
Nominal Active Power of Load C	100.5 MW
Nominal Active Power of Load 2	126.875 MW

C. Resilience Index

The resilience concept, as an alternative to the traditional risk management, has gained importance, especially in the last decade. An overview of the method developed in the project ResiliEntEE is presented in this section [23]. The concept is based on fundamental ideas from [24].

First, a characteristic variable x with a set point x_{set} that reflects the performance of the considered system is selected. For energy systems, the energy flows to the consumers in the considered sector, i.e. the enthalpy flow rate for the gas sector, the heat flow rate for the heat sector and the active power for the electricity sector, are recommended. The timeseries of this variable are compared for an undisturbed and a disturbed system (Fig. 2). The disturbance starts at t_d and persists until t_r.

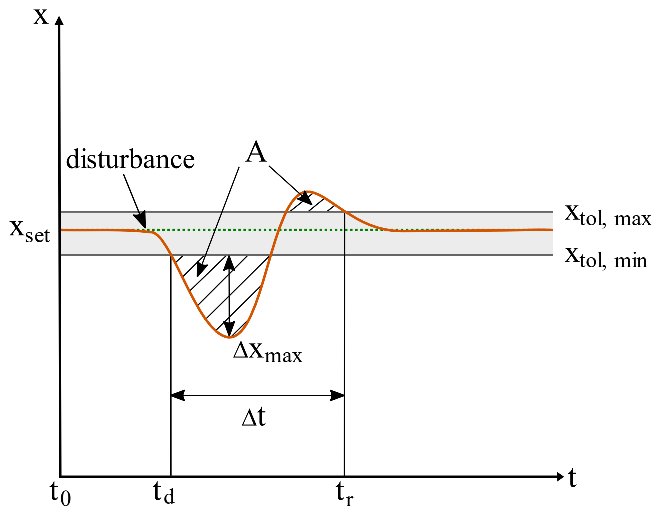

Fig. 2 Comparison of the characteristic value x for an undisturbed (green, dotted line) and a disturbed system (orange, solid line).

Small deviations are accepted by virtue of a tolerance band $x_{\text{tol,min}}$ to $x_{\text{tol,max}}$ around the undisturbed value (grey-shaded area). Deviations outside of the tolerance band are defined as:

$$\Delta x = \begin{cases} x - x_{\text{tol,max}} & \text{if} \quad x \geq x_{\text{tol,max}} \\ 0 & \text{if} \quad x_{\text{tol,min}} < x < x_{\text{tol,max}} \\ x_{\text{tol,min}} - x & \text{if} \quad x \leq x_{\text{tol,min}} \end{cases} \tag{1}$$

The maximum of Δx provides insight into the absorptive capacity of the system. Thus, the Maximum Deviation MD is the first element of the Resilience Index:

$$MD = \frac{\Delta x_{\text{max}}}{\Delta x_{\text{norm}}} \tag{2}$$

Note that all elements will be normalized yielding a dimensionless index. The normalization values need to be chosen carefully. Their choice influences the results significantly. Simulation models with the same structure should only be compared using the same normalization values. Second, the time period during which deviations outside of the tolerance band occur is considered as the Recovery Time ***RT***:

$$RT = \frac{t_{\text{r}} - t_{\text{d}}}{\Delta t_{\text{norm}}} \tag{3}$$

The last element gives additional information on the timeseries curve shape. In the Performance Loss PL, the area outside of the tolerance band (hatched area A in Fig. 2) is considered:

$$PL = \frac{A}{A_{\text{norm}}} = \frac{\int_{t_{\text{d}}}^{t_{\text{r}}} \Delta x \, \text{d}t}{A_{\text{norm}}} \tag{4}$$

These three elements are combined in the Resilience Index:

$$RI = \frac{1}{1 + RT \cdot MD \cdot PL} \tag{5}$$

The Resilience Index is computed for every consumer in the considered sector. Moreover, a sector Resilience Index RI_{sec} as the demand-weighted average of all consumer indices RI_C is defined as

$$RI_{\text{sec}} = \sum_{C} \frac{E_C}{E_{\text{sec}}} \cdot RI_C, \tag{6}$$

with E_C as the energy demand of the consumer during the simulation period and E_{sec} as the overall energy demand of the considered sector during the simulation period.

III. Simulation Results

In the following, three scenarios are investigated.

- The first scenario, referred to as S1, shows the normal operation of the IES under ambient conditions from real weather data for the whole day of January 1st 2012 in Hamburg.
- The second scenario S2 shows a transmission line outage of one of the two double lines between Bus A and Bus B at approximately 3:42 am. This point in time is chosen because the gas grid is in a vulnerable operation state.
- In scenario S3, the CHP plant is turned off at 8:20 am due to a technical problem.

In each presented simulation, the disturbances remain until the end of the simulation after 24 hours. In general, scenarios with the risk of cascading disturbances shall be investigated.

A. System Behavior

In normal operation (S1), the system shows a stable behavior where all electric and heat loads are fully supplied and the operational limits are not violated. In the following plot figures, the disturbance time interval of S2 is marked in light red and the disturbance time interval of S3 in light cyan. The frequency of the electric grid for S1 and S2 are shown in Figure 3. The frequency stays in the interval of 49.98 Hz to 50.04 Hz for S1. The line outage only marginally affects frequency stability in S2. The installed nominal power of the electric grid sums up to 3.3 GW. Thus, the electric grid can be assumed more of an island system rather than an interconnected one. For such an island system, this frequency behavior reveals high frequency stability. This undisturbed scenario is used as reference scenario to define the RI values of S2 and S3 in the following.

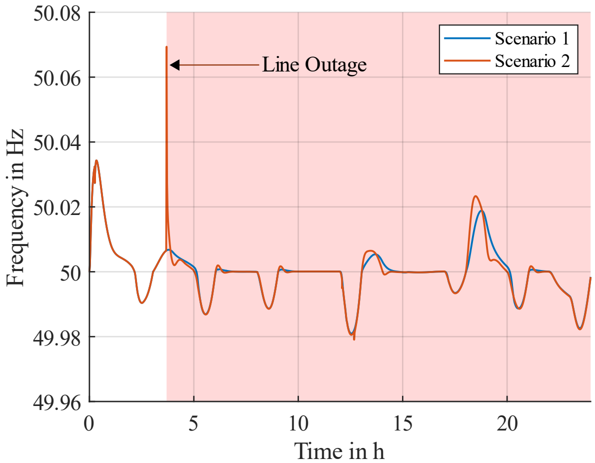

Fig. 3 Electric grid frequency during normal operation (S1) and during line outage (S2).

In S2, the line outage leads to a voltage drop in the electric grid, see Fig. 4. As mentioned before, Bus A shows the lowest voltage stability. Thus, the voltage drop is the highest in comparison to the other busses. Consequently, the electrolyzer is switched off. Nevertheless, the voltage stability is maintained. The OLTC for Bus A needs to tap twice after approximately 12 h to hold the secondary side voltage in the tolerance band of ± 2.5 % of the nominal voltage. In the gas system, the gas pressure drops in normal operation after initialization because of the gas demand of the CHP. The outage of the electrolyzer leads to a small drop of 0.14 bar in gas pressure. The heat system is not affected by the line outage. Fig. 5 shows the gas pressure at the CHP for all scenarios.

In the third scenario (S3), the CHP plant is turned off at 8:20 am due to an internal failure and stays in that condition until the end of the simulation. This failure has numerous consequences. Due to higher transmission line usage, the voltage at Bus A decreases, but stabilizes. In comparison to S2, the voltage stays above 109 kV for the whole simulation and the electrolyzer can maintain operation (Fig. 4). The voltage at Bus A decreases again because of higher transmission line usage. The biomass power plant needs to supply the electric boiler, too. Obviously, the frequency drops due to the imbalance in generation and consumption. The control reserve of the biomass power plant is able to stabilize the frequency and the frequency drop is limited to 49.48 Hz, see Fig. 6. As a consequence of the disrupted heat supply, the energy from the heat storage is used for serving the heat demand of the heat consumers. The energy stored in the heat storage reduces continuously. Hence, the electric boiler is switched on at 9:43 am. This leads to a second frequency and voltage drop. With a value of 49.3 Hz, the frequency shows even less stable behavior than in the CHP plant outage. Furthermore, the gas pressure at the CHP increases because the electrolyzer is not switched off and continues to produce H_2. It is assumed that the hydrogen is also needed for other purposes. The gas boundary defines temperature, mass composition and pressure. Hence, the gas flow is not determined allowing a bidirectional gas flow for absorbing the produced hydrogen.

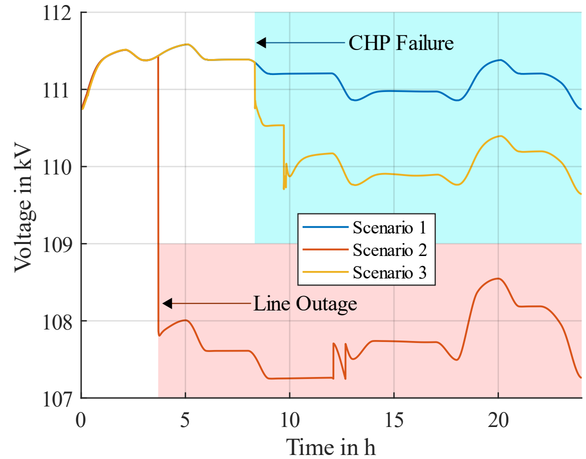

Fig. 4 Voltage at Bus A (secondary side) in all three scenarios.

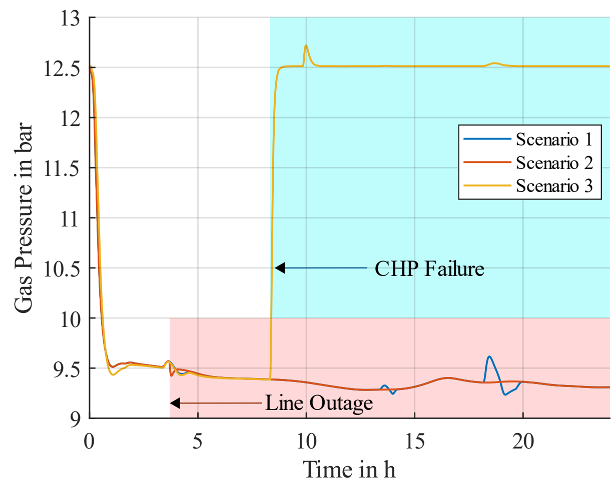

Fig. 5 Gas pressure at CHP in all three scenarios.

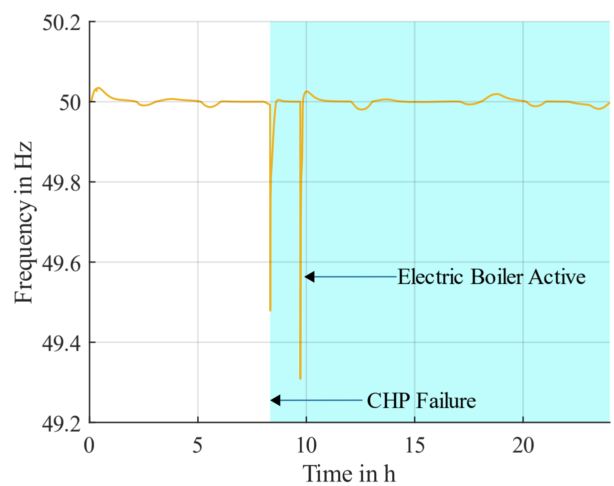

Fig. 6 Electric grid frequency during CHP outage (S3).

In the heat system, the heat consumer's room temperature decreases only marginally, leading to no comfort losses for the residents. Even without the activation of the electric boiler, the room temperature remains above 19 °C because of the heat supplied by the hot water storage. Here, the impact of the high time constants compared to the time constant in electric grid operation caused by the high heat capacities of the buildings and the hot water storage become apparent. Hence, the heat sector reveals low sensibility to disturbances and dynamic interactions. Figure 7 shows the room temperature for the undisturbed S1 and for the CHP plant outage in S3.

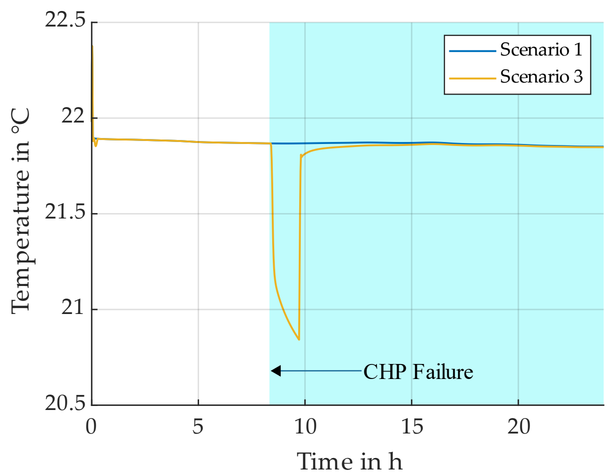

Fig. 7 Room temperature in households in S1 and S3.

B. Resilience Assessment and Discussion

The results clearly show that dynamic interactions have a significant influence on the time behavior of relevant variables in IES. In the regarded scenario, stable operation is possible due to the frequency control of the power plants. The heat supply is maintained with the activation of the electric boiler which is done manually. In the scenario in which a transmission line outage is applied (S2), the electric subsystem is affected with only small influence on the other sectors. In the gas grid, the gas pressure decreases slightly due to the shutdown of the electrolyzer. This drop has no effect on the operation of the CHP plant and the electrolyzer. Because the heat system is fully supplied by the CHP plant, there is no deviation to the undisturbed reference scenario (S1). Hence, dynamic interactions between the subsystems occur but do not influence operation. Such disturbances are defined as intra-sector disturbances. In the scenario with the CHP plant failure (S3), all three subsystems are influenced by the disturbance. Dynamic interactions occur between all the subsystems and have a visible effect. These disturbances are defined as inter-sector disturbances.

Based on the simulation results, the Resilience Indices are calculated according to Section II. First, the characteristic variables are selected as the active power for the electricity sector, the enthalpy flow rate for the gas sector and the heat flow rate for the heating sector. In the described method, the non-disturbed scenario S1 is used as reference. Hence, the tolerance band is chosen relatively to the actual time value of the characteristic variable in S1 with a deviation of 10 % for the heat and gas sector and 1 % for the electrical sector. The tolerance band is less strict for the gas and the heat sector because the sectors can buffer disturbances for a longer time. Δx_{norm} is defined as the maximum possible deviation at the point of maximum occurring deviation. Additionally, the normalization value Δt_{norm} is chosen as the duration of the disturbance. This tolerance band and the normalization values are chosen as declared in [23]. For A_{norm}, the product of Δt_{norm} and Δx_{norm} is used.

For S2 and S3, the Resilience Index values cannot represent the disturbance in the electric sector. The reason for this is the consideration of the consumed active power at the loads. Although the consumed active power at the loads is frequency and voltage dependent, the control mechanisms for frequency and voltage are able to hold or restore these two quantities within a relatively short time frame compared to the duration of the disturbance. Therefore, there is no significant deviation from the active power consumption. Moreover, the consumed power does not reflect the stability of the electric grid. Hence, frequency and voltage values are more suitable for analyzing the respective stability phenomenon. In the context of the resilience index, these quantities can be used as characteristic variables instead of the consumed active power [25], which is also recommended in [23].

Applied to the simulation results for the transmission line outage in this paper, the normalization values are chosen as stated in [25]. This implies that a 50 mHz tolerance band around 50 Hz with normalization values of $\Delta x_{norm} = 150$ mHz and $\Delta t_{norm} = 5$ s are is selected. The voltage band of ± 5 % of the nominal voltage is not exceeded in this scenario since the OLTC controls the secondary side voltage properly. Hence, the normalization values for the voltage are not relevant at this point. The Performance Loss is ignored in those calculations as proposed in [25]. Thus, there is no A_{norm} to determine. Table II shows the selected normalization values for the calculation of the Resilience Indices:

TABLE II
NORMALIZATION VALUES OF RESILIENCE INDEX CALCULATION

Normalization Value	**Sector**			
	Electricity: active power	*Electricity: frequency/ (voltage)*	*Gas: enthalpy flow rate*	*Heat: heat flow rate*
Δx_{norm}	99 % of value in S1	150 mHz	90 % of value in S1	90 % of value in S1
Δt_{norm}	duration of the disturbance	5 s	duration of the disturbance	duration of the disturbance
A_{norm}	$\Delta t_{norm} \cdot \Delta x_{norm}$	Not necassary	$\Delta t_{norm} \cdot \Delta x_{norm}$	$\Delta t_{norm} \cdot \Delta x_{norm}$

The concept of the Resilience Index is applied to the simulation results and the calculated values are shown in Table III.

TABLE III
NORMALIZATION VALUES OF RESILIENCE INDEX CALCULATION

Resilience Index	**Sector**			
	Electricity: active power	*Electricity: frequency/ (voltage)*	*Gas*	*Heat*
Scenario 2	1.000	0.7344	1.000	1.000
Scenario 3	1.000	2.1650×10^{-4}	0.4159	0.9532

For the CHP plant failure in S3, the Resilience Index of the electric subsystem based on the frequency deviation yields 2.1650×10^{-4}. This is a small value compared to the value for S2, signaling poor resilience of the system. The reason lies in the cascade type of disturbance with the electric boiler switched on 5000 s after the CHP plant failure. The method for the Resilience Index interprets the second frequency drop induced by the electric boiler switch-on as part of the disturbance. This interpretation leads to a Recovery Time of 5400 s divided by $\Delta t_{norm} = 5$ s, which is consequently high. Considering only the two frequency drops as independent disturbances, the resilience would be quantified with higher values of 0.0018 and 0.0030 respectively but still lower than in S2. This shows a starting point for discussion of the presented method for cascaded disturbances.

Another starting point for discussion occurs when one sector is not influenced by a disturbance during an intra-sector disturbance. With the presented method, the Resilience Index is calculated as unity even though other sectors are mainly supplied by and thus dependent on the affected sector. In the context of dynamic interactions, the resilience of this originally unaffected sector can be threatened by the disturbance. This is the case in the scenario with transmission line outage (S2). The nonlinearity of the system can lead to disproportionate severe interactions with only a slightly different system configuration, e.g. if a voltage collapse occurs due to the transmission line outage at higher grid usage. Hence, intra-sector disturbance can become to a thread for other sectors. Therefore, the energy flow between the sectors during the whole simulation should also be regarded to cover interactions and dependencies between sectors. The Resilience index of each sector can be updated by a linear combination of these energy flows and thus, such resilience risks can be integrated to the Resilience Index concept.

Finally, the Resilience Index for the gas sector in the scenario with the CHP plant failure (S3) reveals low resilience although the gas pressure is in a tolerable interval and other gas consumers could be supplied if they existed. For the calculation of the Resilience Index, the gas enthalpy flow rate of the CHP plant is chosen as the characteristic variable because it is the only gas consumer in the IES model. Hence, the Resilience Index represents the behavior of the consumer and not the gas grid. However, the CHP plant is no final consumer but an energy converter between the electric and heat systems. Resilience Index calculations with energy flow quantities as characteristic values can take full insight when the energy consumptions of the final consumers are considered. Generally, final gas consumers are rare in reality since, for example, the gas-fired heat provision of low temperature heat is assigned to the heat sector with its own Resilience Index value. Thus, final gas consumers are limited to applications such as high-temperature heat or non-energetic gas consumption.

IV. Conclusion and Outlook

IES as a concept for future energy systems must be investigated with dynamic simulations to access their stability and security of supply. Dynamic interactions between components in IES can offer flexibility and thus, stabilization on the one hand. On the other hand, dynamic interactions can lead to stability risks in the case of disturbances. In this paper, a concept for the stability and resilience investigation of IES is presented. This concept including the Resilience Index, a quantified measure for resilience, is applied to assess dynamic interactions between the sectors electricity, gas and heat. This is performed for a demonstration model with a vulnerable electric grid in three scenarios. It is confirmed that dynamic interactions occur during disturbances. Only dynamic simulation which is used for the derivation of the results allows the consideration of dynamic interactions in the calculation of the Resilience Index. This concept allows a unified assessment of resilience aspects in IES for all sectors. When using characteristic values representing the energy consumption of consumers for each sector, the Resilience Index concept results in comparable values calculated with the same approach. In contrast, this idea leads to unexpected high values for the Resilience Index for the electric grid as far as no load shedding as a last consequence is conducted. Accordingly, the resilience of the electric grid is investigated with respect to frequency and voltage stability in an additional step. With this approach, more insight to frequency stability is gained.

If dynamic effects and therefore the inertness of system components and controllers were neglected, the interactions cannot be recognized because steady state simulation would only allow to find the disturbance’s consequence in the sector where the disturbance originates from. Additionally, the two sides of dynamic interactions, which lead to flexibility but also stability risks, are demonstrated. On the one side, additional primary sector coupling technologies allow a resilience improvement for one sector by providing redundancy but on the other side, endanger the stability of another sector by using power from.

For upcoming scientific developments, the concept of the Resilience Index should even be further developed. Using the voltage magnitude as a characteristic value for the Resilience Index calculation, the insight to voltage stability is limited. Hence, the usage of voltage stability indicators such as voltage stability indices is planned for future investigations.

Another starting point for further work in the context of the described Resilience Index concept is revealed when disturbances affect only one sector. These disturbances are referred to as intra-sector disturbances. The dynamic interactions are not significant enough to influence the stable operation and thus the Resilience Index. Nevertheless, due to nonlinearities, the system resilience can be threatened without any evidence given by the Resilience Index. It is recommended to consider the energy flows between the sectors in form of continuous inter-sector energy flows. An updated Resilience Index that allows for more insights in potential resilience risks in IES needs to be proposed in the future.

Ultimately, the concept will be applied to larger IES like the Northern German energy system. Such interconnected large-scale systems are more complex than the presented demonstration model. This underlines the necessity of using dynamic simulation in the energy system analysis of IES as done in this paper.

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