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The significance of gas for the resilience of future energy systems

Introduction

Complex energy systems consist of different energy suppliers, users, various energy distribution systems and energy storages which dynamically interact. The optimal architecture of an energy system depends on economical parameters and on the environmental impact. But there is one more aspect which has to be considered in the future. Since more and more fluctuating renewable energies are being introduced into the energy grids, the resilience of an energy system becomes an important criterion, too. In Europe the reliability of the gas, heat and power supply is still high. Nevertheless, there have been some serious incidents in the past which could be seen as a warning not to underestimate the problem of future energy systems, especially if they are pure electrical systems. Up to now the difference between electrical energy supply and demand has been covered by a high amount of surplus energy, mainly supplied by thermal power plants. This will no longer be possible in Germany after the shutdown of nuclear power plants in 2022 and coal fired power plants in 2038. Furthermore, Germany has to significantly reduce the amount of imported fossil natural gas in the near future, which will also have an additional effect on the resilience of the energy system.

Resilience

One aspect to be considered for the assessment of an energy architecture is the resilience. There is a difference between reliability and resilience. Reliability describes the ability of a system to supply the demanded power at a given point of time. Resilience is the ability of a system to rebound after a disturbance [1]. This ability has to be quantified to obtain an indicator like CO_2 emissions for the environmental impact and cost/kWh of useful energy for the economic assessment [2]. Three aspects are taken into consideration to quantify resilience (Fig. 1):

- The *restorative capacity* is described by the recovery time RT of the system, which is the time difference between a characteristic variable first leaving the tolerance band and then permanently returning to it.
- The *absorptive capacity* is characterized by the maximum deviation MD of the characteristic variable from its tolerance band.
- The *adaptive capacity* is expressed by the performance loss PL of the system, which is represented by the area between the curve of the characteristic variable and the tolerance band.

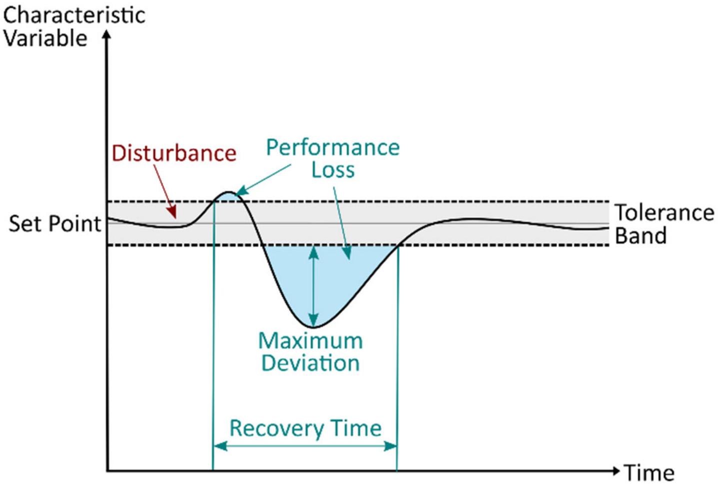

Fig. 1: Behaviour of a system's characteristic variable after a disturbance for a resilient system

Using these characteristic aspects, a resilience index is defined as

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

$RI = 1$ means the considered measure shows only tolerable deviations when the system is disturbed. The system's functionality is not negatively affected negatively by the investigated disturbance.

$RI = 0.5$ means the considered measure shows a total loss of performance during the duration of the disturbance. After the end of the disturbance, the system is able to restore its functionality immediately.

$RI = 0$ means the considered measure does not return to the tolerated deviation range. The system is not able to restore its functionality in the simulated time period.

This resilience index can be calculated for every consumer j in the energy system considered. To gain an overall perspective of the resilience of the individual energy sectors, the resilience indices of their consumers are weighted by their energy demand E during the time period and combined into one sector resilience index.

$$RI = \sum_{j} \frac{E_j}{E_{sector}} \cdot RI_j$$

A crucial point of the resilience index is the selection of a suitable characteristic variable as performance indicator. For energy systems it appears that energy flows like enthalpy flow rate, heat flow rate and electric power are the best performance indicator. Furthermore, the definition of reference values for the deviation from the set point for each performance indicator and for the time is quite important. The definition of the resilience index is described in [2] and in more detail (but in German) in [3].

Assessment of energy systems

The assessment of future integrated energy system architectures has to be carried out by means of system simulation. A suitable method for dynamic system simulation is equation-based modelling. Object-oriented, acausal modelling languages like Modelica [4] help to structure a complex physical system. The acausal approach is crucial for dynamic modelling of energy systems because the input and output of elements like pipes or transmission lines are not clearly defined at the beginning and can change during the simulation. The causality has to be found during the simulation. Physical modelling is necessary because different drafts of energy system architectures have to be assessed where no measurement data are available. Dynamic modelling is necessary because the system's response to disturbances should be investigated. Different time scales have to be considered. In the case of a power grid, seconds are important whereas for gas and district heating grids, changes propagate in minutes or hours. It is therefore not possible to build simple table-based models by measurement data. The object-oriented feature is necessary because component models for complex energy systems are from different physical domains. The system can only be modelled by co-operation between experts with different technical-scientific backgrounds. An example of a tool for dynamic modelling of complex integrated energy systems is the Modelica-based TransiEnt Library [5].

By comparing system architectures and determining the resilience indices it is possible to investigate different disturbances (weather conditions, line breaks, cyber-attacks) and above all else, to gain a better understanding of the system's behaviour. For the assessment it is important to investigate the whole energy system, not just the grids alone. The product which has to be delivered is user energy, for example heat (room heating, warm water, high temperature heat for industry), potential energy (elevators) or kinetic energy (mobile applications). For the user it is irrelevant how this energy is delivered if it is payable. For example, heat for room heating could be delivered by electrically driven heat pumps, by condensing gas boilers or by a combined-cycle power plant with a district heating system.

An exemplary energy system

The applicability of the resilience index is shown for an exemplary energy system (Fig. 2). The user data of the system are approximately equivalent to energy systems of small towns like Oldenburg in Germany. The main purpose of this system is not to depict a real energy system, but rather to prove the applicability and specifics of the resilience index. It is not suitable to make a fair comparison between gas heating appliances and electric heat pumps, since the biomass and the incineration power plants in this exemplary energy system are quite big and their fuel supply (biomass, waste) is ensured.

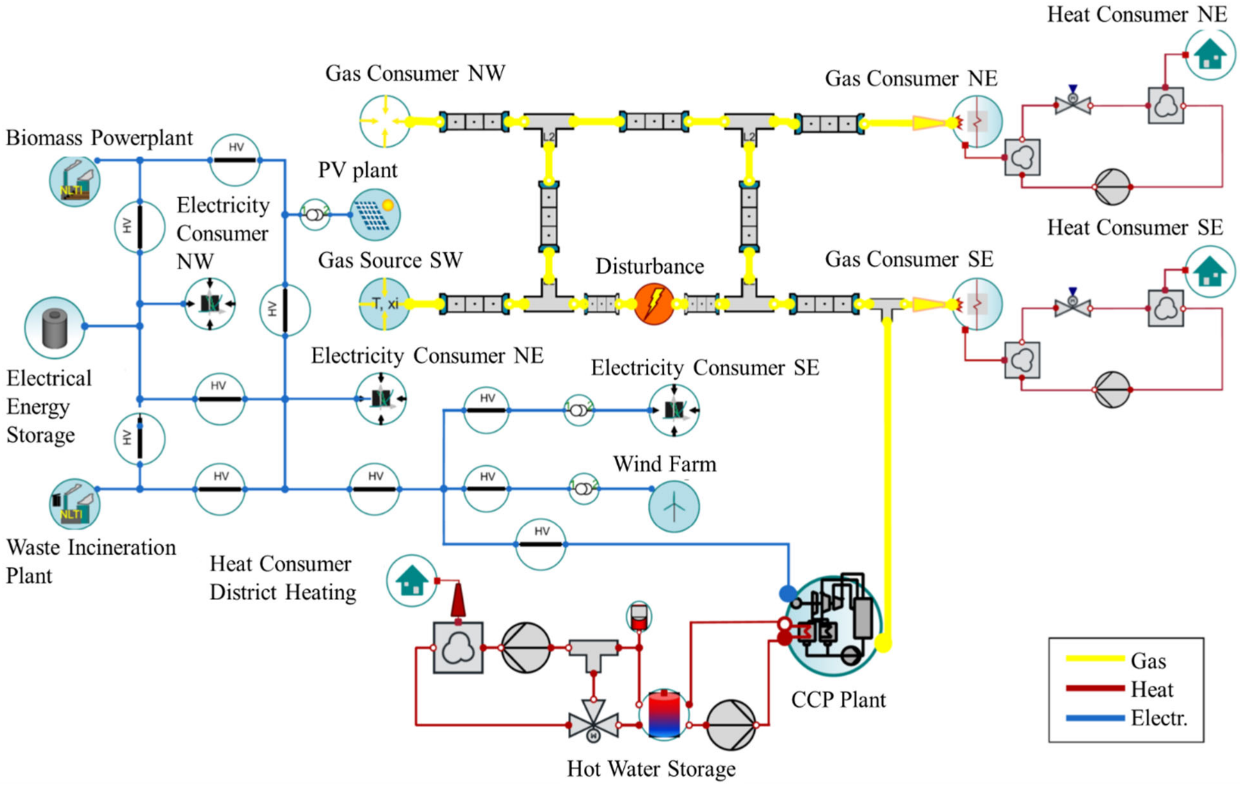

Fig. 2: Exemplary integrated energy system

The key parameters are listed in Table 1. Gas, heat and power are integrated and coupled by a combined-cycle power plant (CCP) with heat extraction. The energy system has different industrial and domestic users at different locations, here they are called North-West (NW), North-East (NE) and South-East (SE). The external energy sources of the system are gas, which could be biogas or synthetic natural gas, local solar energy and wind, biomass and waste. The gas is fed into the grid by a gas source in the southwest (SW). The usable excess heat of the combined-cycle power plant is used to provide heat for a district heating network (DHN).

All gas consumers can take gas from the grid as long as the pressure at the corresponding transfer station is above a given minimum pressure. Otherwise a gas appliance is shut down. The heat sector in the model consists of three sections: two residential areas that are provided with heat by condensing gas boilers, and one residential area where the households are connected to the district heating network supplied by the CCP plant. The reaction of a heating system to disruptions depends significantly on the thermal properties of the houses supplied, as well as environmental effects such as outside temperature, solar radiation or wind speed. The heat flow rate of the CCP plant is controlled to achieve a water temperature of 85°C at the top of the buffer storage. The supply temperature of the DHN is regulated by a back-mixing unit, depending on the outside temperature, following a heating curve with a maximum temperature of 80°C. Temperature data measured in Hamburg in 2012 are used for the ambient temperature.

Parameter	Value
Gas sector	
Feed-In Pressure at Gas Source	12.5 bar
Total Length of the Pipelines	47 km
Heat sector	
Households Gas NE	60,000 households, 300 MW
Households Gas SE	22,000 households, 110 MW
Households district heating	8,345 households, 40 MW @ 80°C
Power sector	
Biomass plant	80 MW
Waste incineration plant	100 MW
Nominal wind power	60 MW
Peak PV power	18 MW
Nominal electric power CCP plant	60 MW
Storage capacity electric energy storage	0.4 GWh$_{el}$

Table 1: Key parameters of the energy systems component [3]

The heat flow rate to all three typical households is controlled to achieve a room temperature of 22°C. In the electric grid, three consumers are implemented whose demand is modelled according to standard load profiles for industry, agriculture and households [6]. The dynamic behaviour of the loads is modelled according to [7]. In this model, the load reacts linearly to the frequency. A distribution of 50% power for heating, 25% for electric motors and 25% for electronics was assumed for the agricultural load. The power demand is covered by wind turbines, photovoltaic (PV), a biomass power plant, a waste incineration plant and the previously-mentioned CCP plant. The operation of the CCP plant is determined by the heat demand of the DHN and the power demand in the electric grid. As long as both values are within the operating range of the CCP plant, both demands can be satisfied. If one of the boundaries is reached, the electric power output or the heat flow rate is limited, which means the CCP plant is controlled by the heat demand.

Furthermore, an electric energy storage like a battery system or one as described by von der Heyde [8] is implemented to absorb possible surpluses of electric energy and avoid curtailment of the renewables. Therefore, the production of the wind turbines and the PV plants only depends on the current solar and wind conditions. The order in which the other plants are used is defined as follows: CCP plant - discharging of the storage – waste incineration plant – biomass plant. Production is controlled according to the grid frequency and thus the current supply and demand in the grid. The models for the transmission lines are quasi-stationary and allow the computation of voltage drops and power losses. More data and modelling details are listed in [3].

Results

A disruption of the gas supply was investigated in order to assess the resilience of the reference system (Fig. 2). A full gas pipeline was closed in the south. This might occur when a component or control unit malfunctions or a gas pipeline ruptures. The duration of the disturbance was set to 14 hours. The starting time of the pipeline closure was selected to be 3:45am on 4 February, since the coldest annual temperatures appear in this period and consequently the heating system is the most vulnerable.

Three system changes to enhance the system's resilience to the disturbance are considered (Fig. 3). They are deemed as alternative ways of providing heat to the customers of the DHN or the customers in the northeast and the southeast. While the first is expected to improve the system's resilience by storages (Resilience Enhancement Measure 1, REM 1), the second increases its decentralization by splitting the CCP plant into two plants (Resilience Enhancement Measure 2, REM 2), and the third raises the diversity of the heat system (Resilience Enhancement Measure 3, REM 3) by adding a heat pump for the heat consumers in NW.

One of these Resilience Enhancement Measures, REM 3, should be considered more in detail. Here, the effects of an electric heat pump as a backup heat supplier in the housing area in the southeast should be studied. The electric heat pump is supplied by the electric network. Its nominal heat flow rate is a little lower than the heat flow rate of the gas boiler.

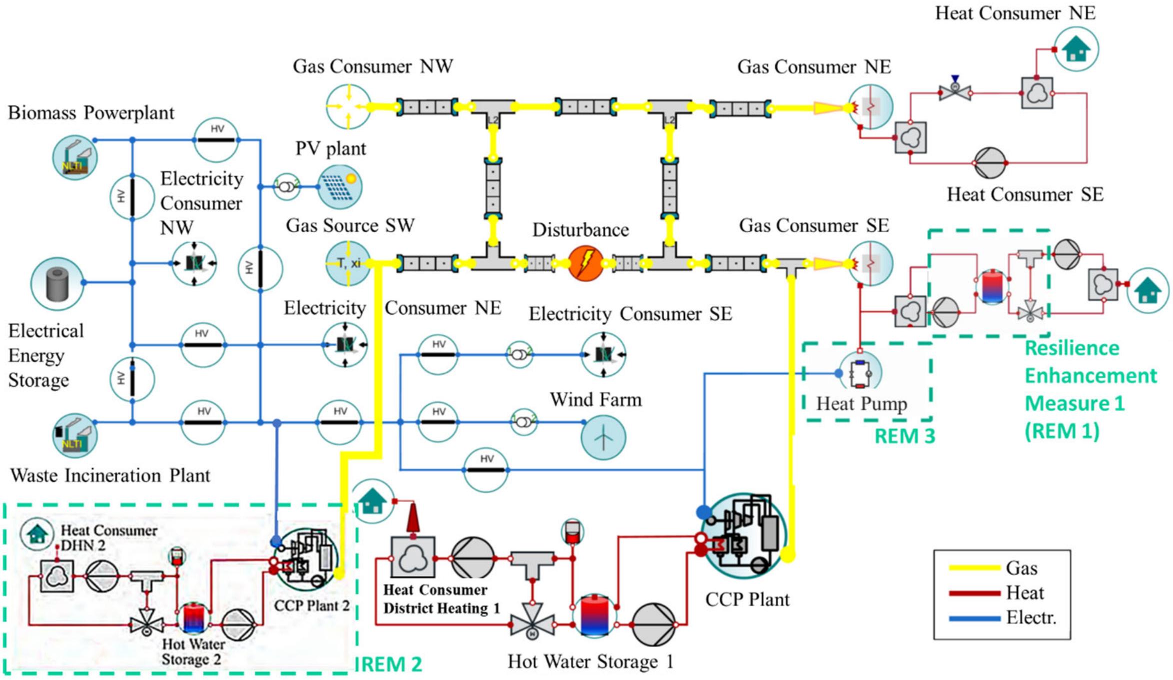

Fig. 3: Resilience Enhancement Measures (REM)

For the reference scenario and REM 3, the simulation results of the dynamic models for a disturbed (solid line) and undisturbed (dashed line) system are presented in Figs. 4 and 5. The curves of gas pressure, room temperature and grid frequency are also depicted to provide a better understanding of the system's behaviour. The enthalpy flow rate (gas sector),heat flow rate (heat sector) and the electric power (power sector) of each system and sector are analysed for the subsequent resilience assessment. These curves are charted as well. Variations of the energy flow rates for the undisturbed situation represent changing boundary conditions like day/night changeover, weather, industrial production demand, etc.
In the reference scenario (Fig. 4), the consequences of the pipeline closure are not only visible in the gas sector but also in the heat and power sectors. When the gas supply in the southeast is cut, the gas pressure in this area drops steeply and boilers and the CCP plant are shut down. This leads to shortages in the heat and power supply that have negative effects on room temperature and power frequency. For the households in the southeast with gas appliances, the gas enthalpy flow rate corresponds to the heat flow rate. Households which are connected to the DHN are supplied in the first hours by the hot water storage, so the room temperature drop is lower. The gas flow rates to the northwest and the northeast do not change. The frequency is barely affected by the pipeline rupture because the incineration plant and the biomass plant are able to deliver the additional electricity demand. The electricity power supply for the industrial consumers in the northwest drops a little.

The improvement in the heating sector by the Resilience Enhancement Measure, REM 3, is visible in Fig. 5. Due to the installation of the electric heat pump, the heating demand of the customers in the southeast can be met at nearly all times. The room temperature hardly drops. This decreases the necessary enthalpy flow rate of this area for reheating purposes after the end of the disturbance and the room temperature quickly reaches the set value. The drop of heat flow rate for the DHN in the southeast corresponds to the drop of the heat flow rate in the reference scenario because the CCP is not affected by REM 3.

Due to the higher demand of electric power for heat pumps and the shutdown of the CCP plant, the incineration plant and the biomass plant are no longer able to deliver sufficient electric power to all customers and the frequency drops significantly. The electric grid is destabilized. In this case, an improvement in one sector causes a deterioration in the other sector, emphasising the necessity of an overall investigation of the system. More detailed descriptions and explanations of the other Resilience Enhancement Measures can be found in [3].

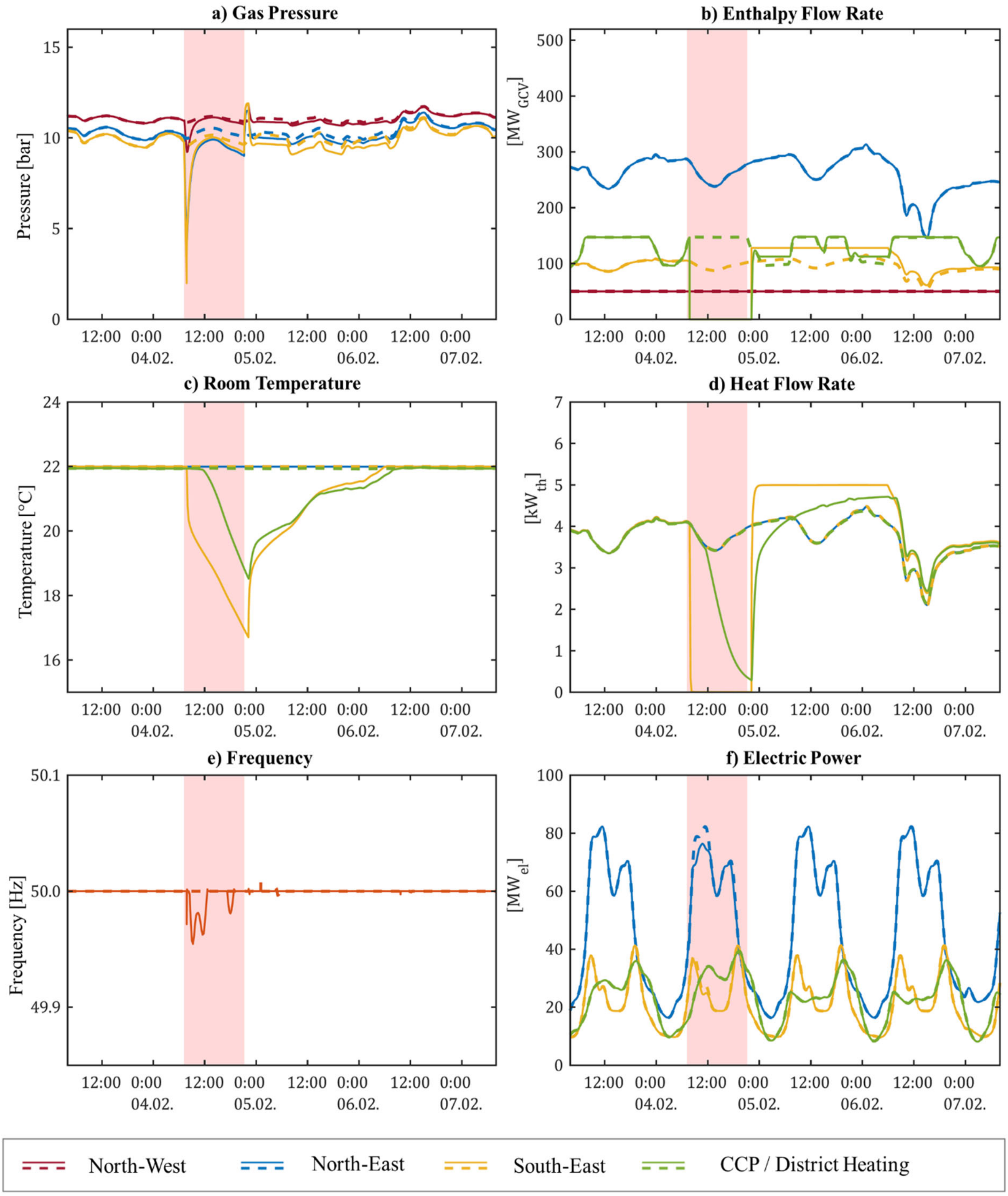

Fig. 4: Simulation results of characteristic values of the gas, heat and power sector for the undisturbed (dashed line) and disturbed (solid line) for the reference system [3]

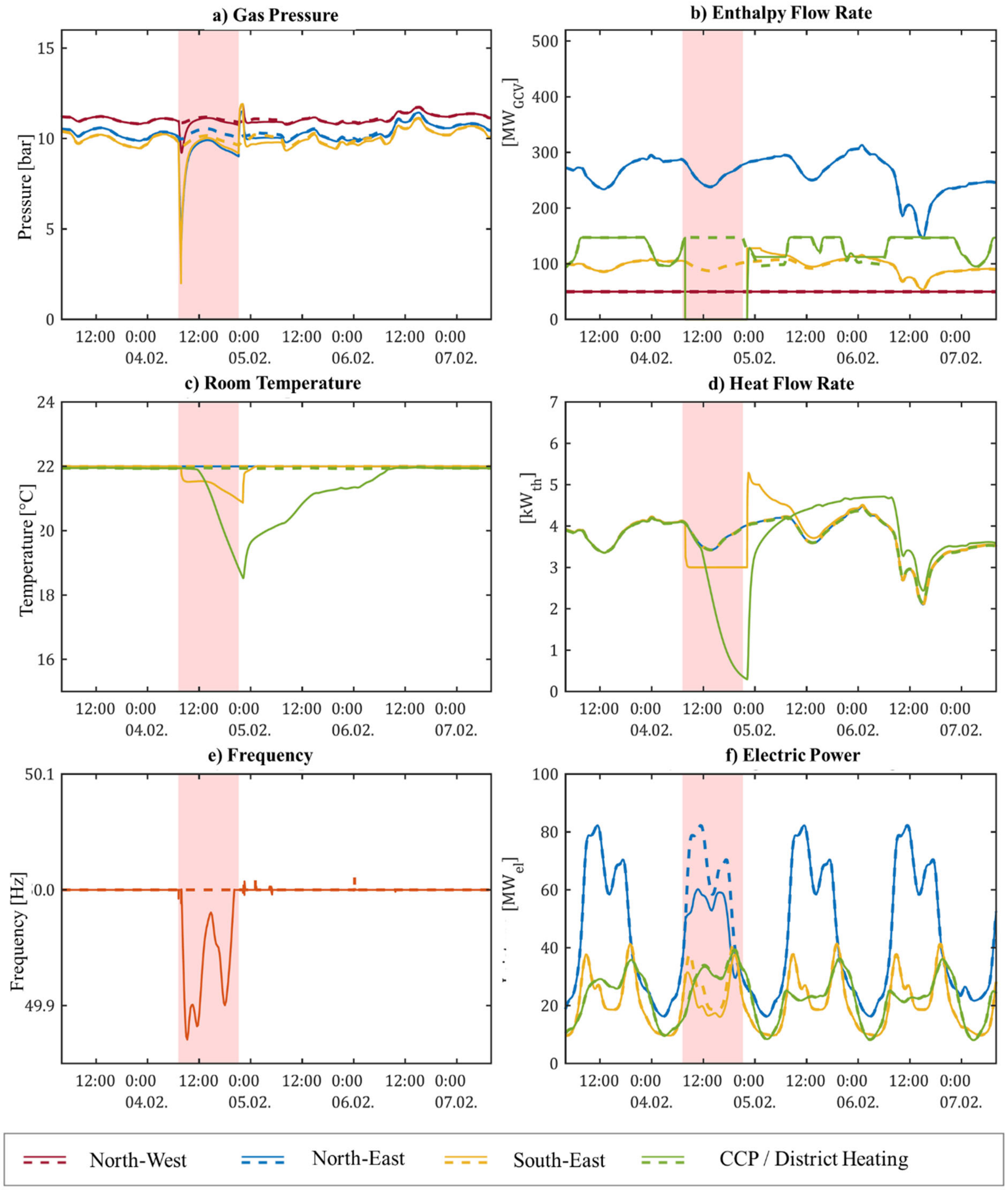

Fig. 5: Simulation results of characteristic values of the gas, heat and power sector for the undisturbed (dashed line) and disturbed (solid line) for REM 3 [3]

Table 2 lists the resilience indices for the reference system and the three Resilience Enhancement Measures. The reference system exhibits the lowest resilience indices for the gas and heat sector, since the heat consumers in particular only depend on one source.

	NW	NE	SE	CCP/DHN	CCP2/HP	Total
			Reference System			
Gas	1.000	1.000	0.163	0.373		0.708
Heat		1.000	0.164	0.366		0.738
Power	0.999	1.000	1.000			0.999
			REM 1 - Storage			
Gas	1.000	1.000	0.138	0.373		0.703
Heat		1.000	0.619	0.367		0.849
Power	0.999	1.000	1.000			0.999
			REM 2 – Two CCPs			
Gas	1.000	1.000	0.172	0.499	0.977	0.789
Heat		1.000	0.175	0.999		0.799
Power	1.000	1.000	1.000			1.000
			REM 3 – Heat Pump			
Gas	1.000	1.000	0.411	0.373		0.754
Heat		1.000	0.955	0.368		0.931
Power	0.953	0.979	1.000		1.000	0.978

Table 2: Resilience indices of consumers and sectors

In the reference system, the CCP plant, the consumers in the southeast and the DHN are not adequately supplied due to the disturbance. For Consumer SE, the resilience indices in the heat and gas sector are nearly the same, since all the gas which is used at this transfer station is used for heating purposes. There is no additional storage in the heating system, which leads to the analogous behaviour in the gas and heat sector. The gas which is used in the CCP plant provides heat and power to its customers. Hence its resilience index for the gas sector reflects the behaviour of its power and heat production. The resilience index in the heat sector of the DHN is higher than in the gas sector because of the hot water storage, which is able to deliver heat to the customers for some hours. Therefore, in contrast to Consumer SE, the enthalpy flow rate to the CCP plant does not increase after the disturbance. The electric power sector seems to be fully resilient but one must bear in mind that the power could be supplied by the incineration plant and the biomass plant in this example, too.

The first Resilient Enhancement Measurement, REM 1, results in a significantly higher resilience index in the heat sector but also in a slight decrease in the gas sector. The hot water storage means a higher mass in the systems which has to be heated up after the disturbance and causes a higher gas demand. An additional economic analysis reveals that there is an optimal size of the hot water storage when increasing the resilience as shown in Fig. 6 [3].

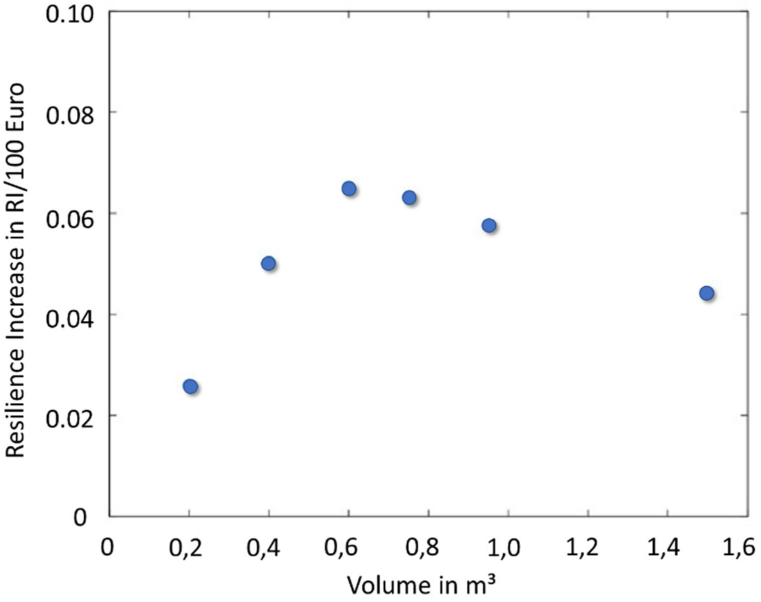

Fig. 6: Resilience enhancement by storage integration (REM 1) per 100 Euro

In REM 2, the splitting of the DHN leads to a slight delay in the shutdown of the gas boiler in the southeast and the original CCP plant in the east. However, since the delay only lasts 18 minutes, the effect on the resilience is not significantly reflected by the resilience indices. Furthermore, since both the original and the eastern DHN/CCP systems are set up similarly and only vary in size, they both react alike, and consequently produce similar resilience indices. The resilience index of the western part of the DHN is one, since it is now supplied by an undisturbed CCP plant. Since the western DHN and CCP plant are supplied without interruption, the overall resilience indices of the heat and gas sector rise. As the western DHN's share of the overall heat consumption is rather low, the increase in the heat sector's index is also small. Nevertheless, the western CCP plant's share of the gas demand is higher. Thus, its undisturbed operation has a greater effect on the resilience index of the gas sector.

In REM 3, the resilience indices of the gas and heat consumers in the southeast rise significantly. Since the electric heat pumps provide the households with the heat flow rate within the given tolerance band, their resilience index in the heat sector is one. As this also leads to a shorter reheating phase, the gas enthalpy flow rate is increased for a shorter time period after the disturbance, leading to a higher resilience index for the gas sector as well. Since the enthalpy flow rate to the gas boiler shows a complete shutdown during the disturbance and a quick recovery thereafter, its resilience index is almost like that of the CCP plant.

However, the negative effects of this additional power demand on the electric grid are reflected by a much smaller resilience index in the power sector, caused by the insufficient power supply to all three consumers. Shifting a sector’s failure into another one can cause massive problems in that sector.

In another paper by Bode [9] based on the TransiEnt – Library, an optimization method was developed to find economical configurations of the future German integrated energy system. This includes a variety of energy storage and heating technologies as well as different power plants. For Power-to-Gas plants, options with and without methanation are considered to investigate the use of either SNG or hydrogen in the gas grid. The economic optimization found hybrid heating systems consisting of electric heat pumps and gas boilers to be the most cost-effective. The electric heat pumps should run with green energy. Even if natural gas is used, the energy for space heating becomes greener when looking to a full period. But in times of very low ambient temperatures, the operation of many electric heat pumps could lead to an overload of the local electric grid. Furthermore, there is often no surplus of green energy during these times.

Hybrid heating systems, like gas condensing boilers with an integrated electric heat pump, will improve the resilience of an integrated energy system. Thus, if a gas grid exists, heat should also be provided by a gas appliance. Of course, hybrid appliances are less economically attractive for gas grid operators because only a small amount of gas is sold during the year. The electrically driven heat pumps run most of the time. The takeover of the gas driven heating appliances during long-lasting cold periods is very important for the resilience of the system, however. In this case, fewer new electric power lines have to be installed.

New business models and innovative economic incentives have to be found to take the system service of gas into account. Customers have to pay a price for energy security and a higher flexibility.

Conclusions

This paper discusses the applicability of the resilience index with the aid of an exemplary energy system which integrates the gas, heat and power sector. The resilience index is a potential way to quantify the resilience of a considered energy system. It is an additional criterion to assess a system such as sustainability (in terms of CO_2 emissions, for example) or economic efficiency (in terms of operating and / or investment costs). It is expected that hybrid systems, like gas condensing boilers with an integrated electric heat pump, will improve the resilience of integrated energy systems. Also, energy hubs with connectors to different energies will improve the flexibility and the resilience of energy systems. Integrated energy network planning tools are necessary to develop new, locally adapted energy system architectures.

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