THE INFLUENCE OF COMBINED POWER, GAS, AND THERMAL NETWORKS ON THE RELIABILITY OF SUPPLY

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Abstract

Modern gas-fired power stations are discussed as an alternative for replacing eventually decommissioned nuclear power stations. With an also increasing number of smallest-scale gas turbines, the importance of the gas network is hence likely to increase in coming years. The presence of converters as e.g. a combined cycle gas turbine raises the question if and to what extent the electrical network will be influenced by the chemical (i.e. gas) and thermal networks and vice-versa. Thus it makes sense to start simulating and analyzing these systems as combined or dependent systems. Furthermore, a user being supplied with electricity from the electrical network and indirectly from the chemical network can choose which network to use. He both has price arbitrage options as well as the option to achieve temporal redundancy of supply.

This paper presents a method developed for investigations of the combined reliability analysis of the electrical, chemical and thermal supply. The applicability of the method is demonstrated with a case example investigating whether a load has a higher availability of supply because of additional indirect supply and whether the reliability of the electrical network could be reduced, because of the local converters helping to maintain the original level of availability of supply.

Keywords: multiple energy carriers, reliability, gas networks, thermal networks

1. INTRODUCTION

In various countries, installations of both small- and large-scale gas-fired power stations are being discussed or take already place. Modern large-scale gas-fired power stations are considered as a viable alternative to new nuclear power stations, replacing ageing ones [1]. The advantages compared with nuclear stations are comparatively shorter construction and amortization times as well as higher flexibility. On the other hand, small-scale gas-fired turbines, also known as microturbines, are promoted for smaller customers as e.g. households or small businesses. Microturbines are providing electricity and thermal energy at the same time, thus using natural gas with a higher overall efficiency compared with single gas turbines or hot water gas boilers.

These trends allow to ask the question if and how in coming years the customer supply with electrical, chemical (i.e. gas) and thermal energy will change. As gas-fired power stations establish a connection between the electrical and chemical network, a certain interchangeability as well as a certain redundancy are being introduced into the system. At certain times it might be financially attractive to generate electricity from gas instead of consuming directly from the electrical network, e.g. during peak hours. Or there could be situations, where it is favorable to make use of the short-term storage flexibility, inherent in the gas network. Altogether, it is likely that peaks from the electrical network will be migrated to the gas network, resulting in a more intensively and differently used gas network. Similar relations and dependencies can be found between thermal network and electrical or chemical networks when considering e.g. hot water boilers or combined heat and power (CHP) gas-fired power stations. Consequently, investigations concerning new and future power systems should incorporate these three energy systems as dependent or combined systems. Therefore, the project *Vision of Future Energy Systems*[1] has been established at the authors' institution in 2003. The project's focus lies on the simulation and optimization of future energy systems, incorporating more than one energy carrier. An important part of the project is the analysis of the influence on the reliability of supply if a load is connected directly or indirectly to different supply systems. As most end-users consume electrical, chemical (i.e. fossil gas or eventually hydrogen) and thermal energy, they are the here considered supply systems. Furthermore, these three supply infrastructures have key characteristics, which complement each other (e.g. short-term storage in gas-networks, latency in thermal networks) and allow synergies to be used.

A major synergy concerns the reliability of supply. The presence of converters between and connections to several independent supply infrastructures raises the question to what extent the availability of supply is affected and whether redundancy effects exist, to be beneficially used. Thus, this paper focuses on the question, how the existence of converters to and from other networks changes the availability of supply. In particular, whether the existence of converters allows keeping a certain overall level of availability, although the reliability of the original connection is being reduced. Such questions are important both for maintenance considerations and for discussions concerning the benefit of distributed generation.

The next sections present the analysis method, which is then applied in a case example to discuss various aspects concerning the availability of supply. The focus lies on an electrical load, supplied directly from the electrical network and indirectly from the chemical and thermal networks.

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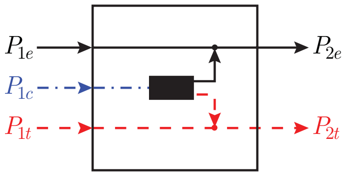
[1] This project is a cooperation with ABB Switzerland, Areva UK, Siemens Germany/Austria, the Swiss Federal Office of Energy as well as the Universities of Delft and Aachen. http://www.eeh.ee.ethz.ch/psl/forschung/vofen.html

2. THE MODELING APPROACH

From a system point of view, a gas-fired power station is simply a converter, converting one form of energy into one or several other forms of energy. Looking at electrical, chemical (e.g. gas) and thermal networks, it is possible to identify various converters between these three systems, as e.g. adsorption coolers, electrolyzers or hot water boilers [2]. In order to have a simple formulation for these conversions, the so-called energy hub modelling concept has been developed within the framework of the project Vision of future energy networks.

According to this modeling approach, any network participant is represented by the energy conversions it is performing. The basic form of an energy hub is thus a two-port, with several energy carriers at its inputs and outputs. Between these ports, the energy carriers are converted into each other, depending on the function of the network participant. The left side of Figure 1 shows a simple example: a combined heat and power plant, generating electricity and heat from gas is reduced to its conversion activities. Each converter relates different forms of energy with each other and can be characterized with its conversion efficiency. This allows introducing a so-called coupling matrix, corresponding to the hub. This matrix has a column for every input carrier and a row for every output carrier. The values at the intersections are then the corresponding conversion efficiencies, also denoted as coupling factors $c_{\alpha\beta}$, coupling the energy carrier α with the carrier β . Like this, the matrix couples the input power flows with those at the output [3]. The right side of Figure 1 shows the coupling matrix resultant from the example. Further dependencies and limitations can be introduced to use this approach for optimal power flow investigations or topology optimizations (for more information please refer to [4]).



$$\begin{array}{c|ccc} & el & ch & th \\ \hline el & c_{ee} & c_{ce} & 0 \\ ch & 0 & 0 & 0 \\ th & 0 & c_{ct} & c_{tt} \end{array}$$

Figure 1. Example of an energy hub representing a combined heat and power plant (CHP), converting chemical energy into electrical and thermal energy.

The model can be extended by allowing more than two ports for an energy hub, with coupling matrices defined for every port-couple. Furthermore, the number of the input and output carriers is arbitrary and does not have to be equal (e.g. a CHP can be represented as a 1x2 matrix). As size and capacity of an energy hub are not limited, any level of detail can be modeled, using this approach to represent a house, a city or also a substation as an energy hub. Theoretically, every entry of the coupling matrix can be non-zero when considering electrical, chemical and thermal networks, although some converter realizations are not yet mature today (e.g. thermovoltaic systems or fuel cells). The general applicability of the approach thus allows modeling any network participant as an energy hub [2, 3].

3. RELIABILITY MODELING

Reliability aspects of an energy hub can be modeled in a similar way to the coupling matrix for conversion efficiencies. Assuming that the operational behavior of an energy hub can be described as a stationary Markov process [5] allows introducing failure and repair rates for all components. Instead of representing a connection between two energy carriers α and β with its conversion efficiency, it can also be represented with both its failure and its repair rate. This leads to a failure rate matrix Λ_{12} and a repair rate matrix M_{12} for every port-pair. The matrix entries are the corresponding failure rates $\lambda_{\alpha\beta}$ and repair rates $\mu_{\alpha\beta}$ of the conversion from α to β , as defined in Eq. (1). Row and column entries correspond to Figure 1.

$$\Lambda_{12} = \begin{bmatrix} \lambda_{ee} & \lambda_{ce} & \lambda_{te} \\ \lambda_{ec} & \lambda_{cc} & \lambda_{tc} \\ \lambda_{et} & \lambda_{ct} & \lambda_{tt} \end{bmatrix} \qquad \mathrm{M}_{12} = \begin{bmatrix} \mu_{ee} & \mu_{ce} & \mu_{te} \\ \mu_{ec} & \mu_{cc} & \mu_{tc} \\ \mu_{et} & \mu_{ct} & \mu_{tt} \end{bmatrix} \tag{1}$$

Each converter is thereby considered as one process that can be in either an operating or a non-operating state. The corresponding state probabilities $R_{\alpha\beta}$ for the up-state and $Q_{\alpha\beta}$ for the down-state can then be defined as [5]:

$$R_{\alpha\beta} = \frac{\mu_{\alpha\beta}}{\lambda_{\alpha\beta} + \mu_{\alpha\beta}}, \quad Q_{\alpha\beta} = \frac{\lambda_{\alpha\beta}}{\lambda_{\alpha\beta} + \mu_{\alpha\beta}} \tag{2}$$

It must be considered here that Eq. (2) concerns the elements covered by the energy hub. This allows choosing whether an analysis should solely focus on the energy hub itself or whether the reliability behavior of the supplying networks should be incorporated as well. Furthermore, single connections inside the hub, e.g. between a converter's output and the receiving network, are assumed to be 100% reliable. The failure and repair rates of direct connections are consequently equal to the failure and repair rates of the network they are connected to. This is a reasonable assumption if the physical dimensions covered by the hub are small.

In order to incorporate the imperfectness of the supplying network, the operating-state probability of e.g. the chemical-electrical converter has to be multiplied with the operating-state probability of the chemical network; they both must be operating for successful supply, forming a series connection. The same holds true for the thermal-electrical path. Eqs. (3) to (5) show the resulting operating-state probabilities of the three paths supplying the electrical load. The factor R_{cc} represents the up-state reliability of the chemical network and R_{tt} that of the thermal network. Those factors can be set equal to 1 or simply omitted for investigations focusing exclusively on the energy hub behavior.

$$R_{ee} = \frac{\mu_{ee}}{\lambda_{ee} + \mu_{ee}} \tag{3}$$

$$R_{ce} = \frac{\mu_{ce}}{\lambda_{ce} + \mu_{ce}} \cdot R_{cc} = \frac{\mu_{ce}}{\lambda_{ce} + \mu_{ce}} \cdot \frac{\mu_{cc}}{\lambda_{cc} + \mu_{cc}} \tag{4}$$

$$R_{te} = \frac{\mu_{te}}{\lambda_{te} + \mu_{te}} \cdot R_{tt} = \frac{\mu_{te}}{\lambda_{te} + \mu_{te}} \cdot \frac{\mu_{tt}}{\lambda_{tt} + \mu_{tt}} \tag{5}$$

Consequently, each of the three outputs can be supplied from theoretically all three networks connected at the hub input. These connections are either direct or indirect and sum up to a total of 9 possible connections between input and output. Each output (i.e. the electrical, the chemical and the thermal load) is thus supplied through three supply paths, each of which can be operating or non-operating. This allows for modeling the supply of every output as a state space diagram with 8 states, representing all possible combinations. Whether a state is a successful state (i.e. the load is supplied) or not, depends both on the capacities of each supply path as well as on the momentary load demand. As long as the load is smaller than the capacity of either a combination of operating components or also just of one operating component, the state is considered as successful. Thus, for the load to be supplied, both the supply paths must be operating and the load must be below their (single or combined) capacities.

As a simplification, it is assumed that connections and converters always operate at their rated power, with an ideal switching behavior. Changing supply situations thus stem from the daily load variations, resulting possibly in momentary situations both with 'n-2' secure supply as well as with 'n-0' secure supply or something in-between.

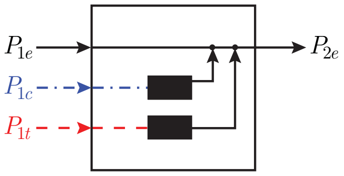


Figure 2. Model of the investigated system: an electrical load, supplied directly and indirectly from electrical, chemical and thermal networks.

The general methods and analysis procedures are the same for all three outputs. For the remainder of the paper, only the electrical output will be considered; the methods can however simply be transferred to the chemical or the thermal output. An electrical load P_{2e} is supplied directly through a connection from the electrical network (P_{1e}) and indirectly through converters from the chemical and from the thermal networks (P_{1c} and P_{1t} respectively). The inputs of this hub are thus electrical, chemical and thermal energy; the considered output is electrical energy only (see Figure 2). From the viewpoint of the electrical load or output, the indirect supply paths can thus be considered as assisting or back-up systems. The chemical-electrical converter most likely has a second, thermal output, which is why the restriction on the electrical output is purely methodological. It is also obvious that when modeling the converter as one process - as suggested here - some entries in the failure and repair matrices will be identical (e.g. $\lambda_{ce} = \lambda_{ct}$ for a micro-turbine).

4. OUTPUT AVAILABILITY AS A FUNCTION OF THE PRESENT COMPONENTS

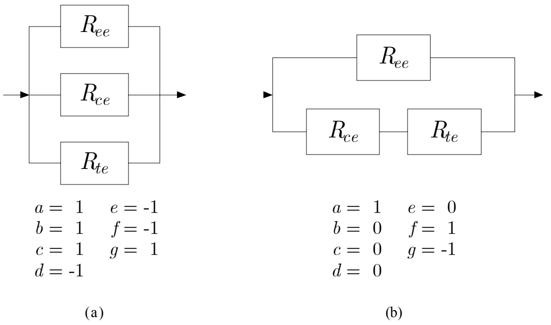
The aim of this study is to derive one formula, which describes the reliability at the output as a function of the hub components' reliability characteristics. The formula should be defined in a way suitable for simulation software applications as e.g. MATLAB®. It can then be used for sensitivity analyses concerning the dependency of the output reliability from various hub configurations. This investigation does not focus on specific conversion technologies and implementations but rather just considers the conversion processes in general. Hence, the focus will lie e.g. on the comparison of the failure rate of the chemical-electrical conversion relative to the direct electrical connection and not on the comparison between e.g. the failure rates of fuel cells and those of microturbines. Thus, for such rather fundamental considerations basic reliability methods and models can be applied.

Based on the Markovian approach, the up-state probability of each of the 8 mentioned operating states can be calculated in terms of failure and repair rates of the different connection paths, as in Eqs. (3) to (5). This can be achieved by using minimal cut sets or tie sets - the final result is the same [6] and both approaches have actually been applied wherever more appropriate. Each of those up-state probabilities consists of 1 to 7 terms, which can be summarized in one formula. Eq.(6) shows this formula, representing all situations from true series connections (load can only be supplied when all connections are operating) to true parallel connections (load can be supplied as soon as one connection is operating).

$$\begin{aligned} R_e &= a \cdot R_{ee} + b \cdot R_{ce} + c \cdot R_{te} + d \cdot R_{ee} R_{ce} \\ &\quad + e \cdot R_{ee} R_{te} + f \cdot R_{ce} R_{te} + g \cdot R_{ee} R_{ce} R_{te} \end{aligned} \qquad (6)$$

$$a, b, c \in [1, 0]; \quad d, e, f \in [1, 0, -1]; \quad g \in [2, 1, 0, -1]$$

The appropriate values for the factors a to g can be found e.g. through a look-up table, comparing the momentary load level with the installed capacity of each installed converter or connection. As an example, Figure 3 shows an abstract representation of two different supply situations with the corresponding values for the parameters a to g.



(a) (b)

Figure 3. Examples of different load supply situations: (a) A load smaller than any of the installed components, corresponding to a parallel supply situation. (b) A load smaller than either the electrical connection or the chemical-electrical and thermal-electrical together. Neither the chemical-electrical nor the thermal-electrical are able of supplying the load alone.

If the connection capacities and their relative sizes are not known, 18 different supply situations exist, covering all combinations for parallel, serial and mixed connections. With the capacities known, a maximum of 7 different supply levels can be identified, assuming that all connections have different capacities. Figure 4 displays an example of a residential load curve and the capacity levels of the three supply paths electrical C_{ee}, chemical-electrical C_{ce} and thermal-electrical C_{te}, assuming $C_{ee} > C_{ce} > C_{te}$. It additionally shows the different combined capacities of e.g. the electrical connection together with the chemical-electrical supply $C_{ee} \wedge C_{ce}$. During period Δt_1, the load can be supplied by any of the three supply paths. During Δt_2 however, none of the supply paths is capable of supplying the load alone; the direct electrical connection and at least one of the indirect connections must be operating

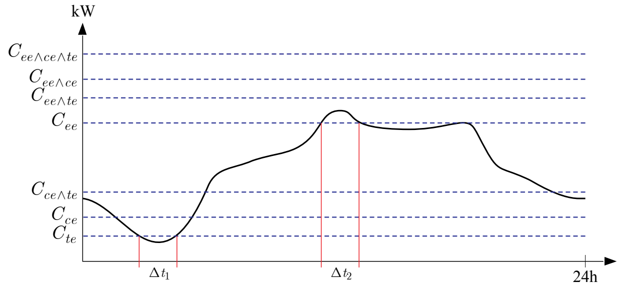


Figure 4. Exemplary load curve, showing the different connection capacities $C_{\alpha\beta}$ and the resulting supply situations.

For a given load or duration curve and a given hub configuration, including the reliability characteristics, the expected reliability of supply at the output can be determined according to the following procedure:

(1) determine the supply capacities of the different connections and combinations of connections in the hub

(2) determine the factors a to g (see Eq. (6)) for every measurement point of the load curve of length n and store them in a $n \times 7$ matrix $\mathbf{F}$, called factor matrix

(3) determine the average occurrence of every factor by summing-up matrix $\mathbf{F}$ column-wise and by dividing by the length, resulting in an 1×7 array $\mathbf{C}$, containing seven entries between 0 and 1

$$\mathbf{C} = \frac{1}{n}\left[\sum_{i=1}^{n}\mathbf{F}(i,1) \quad \sum_{i=1}^{n}\mathbf{F}(i,2) \quad \ldots \quad \sum_{i=1}^{n}\mathbf{F}(i,7)\right] \qquad (7)$$

(4) define a vector $\mathbf{R}$, containing the up-state probabilities associated with the factors a to g in Eq. (6)

$$\mathbf{R} = \begin{bmatrix} R_{ee} & R_{ce} & \ldots & R_{ce}R_{te} & R_{ee}R_{ce}R_{te} \end{bmatrix}^{\mathrm{T}} \qquad (8)$$

(5) the reliability of supply R_{2e} of load P_{2e} is then calculated as

$$R_{2e} = \mathbf{C} \times \mathbf{R} \qquad (9)$$

As vector $\mathbf{R}$ can both be numeric or symbolic, the result could also be expressed in terms of e.g. the chemical-electrical failure rate for a sensitivity study. To illustrate this procedure, an example is presented, before the section with sensitivity analyses follows.

5. EXAMPLE

Figure 5 shows the German standard weekday electrical load profile for a small business with a total annual consumption of $20\,MWh$ [7]. The characteristics of the connections are shown in Table 1. The load curve consists of 15 min. measurements, summing up to a total of 96 intervals. Various technologies for decentralized conversions from chemical to electrical and from thermal to electrical exist, but all yet lack intensive use and consequently reliable failure statistics. This is why the failure and repair rates of these converters are expressed as functions of the failure and repair rates of the electrical connection. In addition, this also allows for deducing minimal requirements for the outage rate of such converters, relative to the performance of the electrical system. The connection capacities C_{ce} and C_{te} as well as the factors x_1 to x_4 (see below) are assumptions, based on information from current publications [8-10].

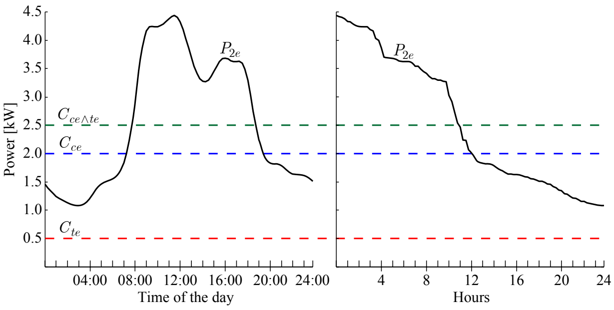


Figure 5. Load curve (left) and duration curve (right) of a load supplied with connections according to Table 1.

Table 1. Connection characteristics.

Connection	Capacity	Failure rate [f/y]	Repair rate [repairs/y]
electrical	$C_{ee} = 10\,kW$	$\lambda_{ee} = 0.5$	$\mu_{ee} = 4380$
chemical-electrical	$C_{ce} = 2.0\,kW$	$\lambda_{ce} = x_1 \cdot \lambda_{ee}$	$\mu_{ce} = x_2 \cdot \mu_{ee}$
thermal-electrical	$C_{te} = 0.5\,kW$	$\lambda_{te} = x_3 \cdot \lambda_{ee}$	$\mu_{te} = x_4 \cdot \mu_{ee}$

The values in Table 1 indicate that the load can always be supplied from the electrical network. Between 19:45 and 7:15, the load is below $2.5\,kW$ and can also be supplied through the additional converters, contributing to the overall availability of supply. Without the energy hub present, i.e. only with the electrical connection, the expected annual outage time would be roughly 1h, corresponding to an unavailability of 1.14E-4 (according to eq. (3)). The failure rates of the chemical-electrical and of the thermal-electrical systems are assumed to be 3 times larger ($x_1 = x_3 = 3$) and the repair times to be 12 times larger ($x_2 = x_4 = 1/12$).

The factors a to g can now be determined for every time step in the load curve. Table 2 contains an excerpt of matrix $\mathbf{F}$, showing the supply level transition between 18:45 and 20:00 (see Figure 5 left). During time steps 76 to 78 the load can either be supplied through the direct electrical connection or indirect through the chemical-electrical connection together with the thermal-electrical connection, corresponding to Figure 3(b).

Table 2. Excerpt from matrix $\mathbf{F}$.

variable	time step	a	b	c	d	e	f	g
	.	.	.	.	.	.	.	.
F	75	1	0	0	0	0	0	0
	76	1	0	0	0	0	1	-1
	77	1	0	0	0	0	1	-1
	78	1	0	0	0	0	1	-1
	79	1	1	0	-1	0	0	0
	.	.	.	.	.	.	.	.

The array $\mathbf{C}$ is then found according to Eq. (7) as

$$\mathbf{C} = \left[1 \quad \frac{47}{96} \quad 0 \quad -\frac{47}{96} \quad 0 \quad \frac{5}{96} \quad -\frac{5}{96}\right] \tag{10}$$

And thus, the reliability of being able to supply the load P_{2e} is found according to Eq. (9) as the product of array $\mathbf{C}$ and vector $\mathbf{R}$.

$$\begin{aligned} R_{2e} = \mathbf{C} \cdot \mathbf{R} = R_{ee} &+ \frac{47}{96} \cdot R_{ce} - \frac{47}{96} \cdot R_{ee} R_{ce} \\ &+ \frac{5}{96} \cdot R_{ce} R_{te} - \frac{5}{96} \cdot R_{ee} R_{ce} R_{te} \end{aligned} \tag{11}$$

Incorporating the values from Table 1 and replacing the variables $R_{\alpha\beta}$ as defined in Eq. (3) to (5), assuming ideal chemical and thermal networks, results in an an expected annual outage of 0.46 h or 27.6 min. This corresponds to an unavailability of 5.26E-5. Compared with the reliability of supply without the energy hub, i.e. without the converters from the chemical and the thermal networks, the unavailability is thus reduced by roughly 46%.

To confirm Eq. (11), the following relations can be identified. According to Figure 5, the load is supplied with three different supply situations during the day with different occurrences (see Table 3). E.g. during the period, where the load is below $2\,kW$, it can be supplied both directly from the electrical network or indirectly from the chemical network. Thus, a parallel or redundant supply exists, whose up-state reliability is defined as [6]

Table 3. Supply level occurrence.

Load level P_{2e} [kW]	supplied by	occurence
$P_{2e} < 2.0$	C_{ee}, C_{ce}	47/96
$2.0 < P_{2e} < 2.5$	$C_{ee}, C_{ce \wedge te}$	5/96
$2.5 < P_{2e}$	C_{ee}	44/96

$$R_{up} = R_{ee} + R_{ce} - R_{ee} R_{ce} \tag{12}$$

Similarly, the up-state reliabilities of the other two supply situations can be identified. Weighting these relations by their occurrence and summing up results in the same outcome as Eq. (11).

6. APPLICATION TO SENSITIVITY ANALYSES

As already mentioned, the presented analysis method can be both used numerically or symbolically. This chapter thus contains various sensitivity analyses showing both the applicability of the method as well as the influence of the energy hub parameters on the reliability of supply.

The first analysis investigates the influence of the failure rate of the chemical-electrical connection on the expected annual outage. Hence, the factor x_1 is varied and the factors x_2 to x_4 are set to the same values as in the example. Varying the failure rate of the chemical-electrical connection from one failure in two years to one failure daily, keeping the repair rate always at 365 repairs/year, results in a dependence of the reliability of supply as shown in Figure 6. Even if the chemical-electrical connection would fail once a day, the expected annual outage would still be lower than without this indirect connection (44 min). Looking at the failure rate of the thermal-electrical connection reveals a significantly lower dependency, as shown in Figure 6 as well. This was expected as the thermal-electrical connection only was supportive during 5 time intervals and even then only if the chemical-electrical connection was operating as well.

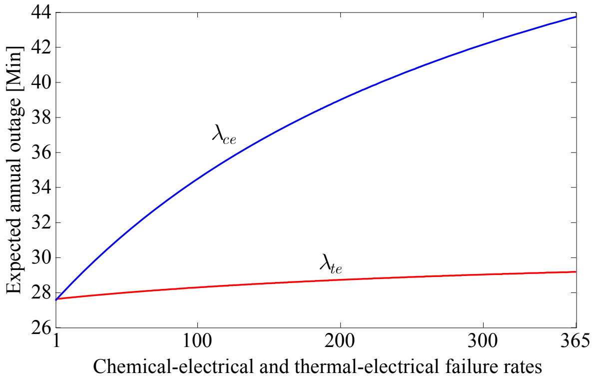


Figure 6. Sensitivity of the expected annual outage to λ_{ce} and to λ_{te}

The peak of the load curve in Figure 5 is at approximately $4.5\,kW$. Both the chemical-electrical and the thermal-electrical connection thus only contribute during low-load periods. Figure 7 shows the influence of a larger chemical-electrical converter on the expected annual outage, the other values being equal to those in the example. Clearly, with the load curve being mostly below $4\,kW$, an installed capacity of the chemical-electrical converter above $C_{ce} = 4\,kW$ will not improve the expected outage. However, the contribution of capacities below that level is well identifiable.

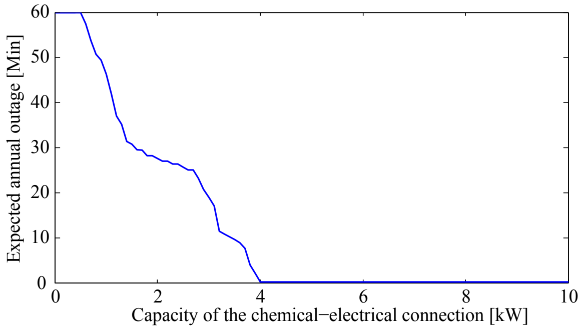


Figure 7. Sensitivity of the expected annual outage to the capacity of the chemical-electrical connection C_{ce}

Distributed or local generation is often claimed to increase the reliability or to at least reduce the reliability requirements on the electrical network. To analyse this, the expected annual outage was defined to always be equal to the expected annual outage without an energy hub present (i.e. roughly $1\,h$, see section 5), such that the load would not sense any difference. Then, the maximum acceptable failure rate of the electrical connection λ_{ee} was calculated for increasing capacities of the chemical-electrical connection C_{ce}. The result is displayed in Figure 8, focusing on the range below $C_{ce} = 4\,kW$. The dotted line represents the failure rate $\lambda_{ee} = 0.5$ without an energy hub. As soon as the capacity exceeds $C_{ce} = 1\,kW$, part of the load can be supplied redundantly and the acceptable failure rate starts to increase. As the capacity goes towards the maximum of the load curve, the minimal λ_{ee} increases significantly.

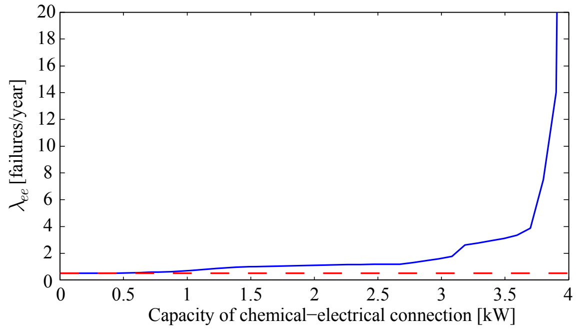


Figure 8. Maximum accepted failure rate of the electrical connection λ_{ee} for an increasing chemical-electrical connection capacity C_{ce} to still maintain the original expected annual outage.

In the example, the energy hub (i.e. the converters) only contributes to the availability of supply during low load periods. Therefore, the following and last sensitivity analysis considers not just the expected annual outage time but also the expected energy not supplied (ENS)[5]. ENS at the electrical output is defined as

$$ENS_{2e} = \frac{1}{N}\sum_{t=1}^{N} P_{2e}(t)\cdot(1-R_{2e})\cdot 8760h \qquad (13)$$

Without an energy hub present, i.e. without converting connections from other supply systems, the expected energy not supplied can be calculated to be $ENS_{2e} = 2.55\,kWh$. With the energy hub present, ENS is reduced to $ENS_{2e} = 1.18\,kWh$.
The influence of the capacity of the chemical-electrical connection C_{ce} is shown in Figure 9. For capacities below $C_{ce} \approx 1\,kW$ no contribution can establish. Above that limit however, the energy not supplied decreases similar to the shape of the duration curve (see Figure 5). The sensitivity is slightly lower around $C_{ce} \approx 2\,kW$ – as indicated by the flatter slope – because the load is rather above $C_{ce} = 1.8\,kW$ or below $C_{ce} \approx 3\,kW$.

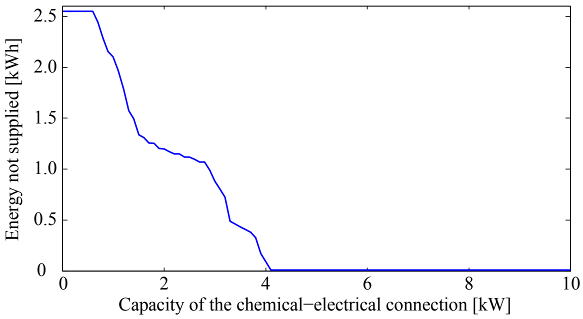


Figure 9. Expected energy not supplied as a function of the chemical-electrical connection's capacity C_{ce}.

Equation (13) considers a load as lost or not supplied if it cannot be fully served; i.e. partial load serving is not considered. However, if the electrical supply would fail during a peak in the load curve (see Figure 5), a base load of maximum $P_{2e} = 2.5\,kW$ could still be supplied with a certain probability. The same holds true for loads below the capacities of the chemical-electrical and thermal-electrical connection. As the usefulness of a partial supply of the load depends on the load itself, this approach is however not considered in this study, but will be subject of further investigations

7. CONCLUSION

A method for the combined analysis of reliability aspects of electrical, chemical and thermal networks has been proposed. The applicability of the method has been demonstrated with a case example, which showed that even low capacity distributed generators with comparatively low reliability characteristics help improving the expected availability of supply at an output. Furthermore, the method was showed to be applicable both for numerical as well as for symbolical investigations.

Following from the results of the case study, distributed generation with already comparatively low installed capacities allows reducing the reliability of the electrical connection, e.g. by increasing the maintenance intervals or by increasing the mean time to repair.

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