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Assessment of Grid and System Supportability Based on Spatio-Temporal Conditions—Novel Key Performance Indicators for Energy System Evaluation

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Abstract: The energy transition introduces new technical standards, laws and regulations regarding the stability and reliability of energy grids and systems. Due to the non-existence of a measuring standard, key performance indicators (KPIs) were developed to enable the measurement and comparison of individual energy grid (namely electricity, heat and gas grid) and system supportabilities while also promoting well-founded decision-making and optimization efforts. Inconsistencies in definitions concerning fundamental energy terms and the correlations between them inhibit the effective usage of the KPIs. Therefore, the overarching issue of the security of energy supply and its related subjects were also approached. The primary subject of this paper is the development of two new KPIs to measure and compare the energy grid and system supportability. These KPIs are based on spatio-temporal conditions in their respective grids. The usage and benefits of the developed KPIs are exemplarily highlighted by analyzing the impact of a scenario with the integration of a large-scale heat pump into the electricity and heat grid. The energy grid supportability is determined for each grid, whereas the energy system supportability takes the interactions of the electricity and heat grid into account. The developed KPIs are intended to enable stakeholders to identify areas with optimization potential in energy grids and systems. Moreover, the KPIs can be used to create a standardized evaluation method for regulatory requirements.

Keywords: key performance indicator (KPI); KPIs in the energy sector; grid supportability; system supportability; energy systems

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1. Introduction

With the advancing energy transition and further geopolitical changes affecting the international energy economy, professional and public interest in the security of energy supply and energy systems is constantly growing. Therefore, the importance of a specific description of energy systems increases. Moreover, with electrification, sector coupling and the connection of new or additional generators and loads to the electricity grid (e.g., electrolyzers, heat pumps, charging infrastructure), the degree of interconnection and, thus, the public relevance, mainly of the electrical energy system, continues to expand.

Analysis and comparison of different energy systems are crucial for a successful energy transition. The comparison of the advantages and disadvantages of different energy storage options could serve as an example of such a necessary approach.

For this, uniform definitions for the assessability of different systems are required, yet energy systems are currently described and characterized imprecisely. As a result, these terms are not used consistently by the general public, politicians or experts, preventing a unified understanding [1] (p. 2).

In order to solve this problem, this paper initially defines standardized terms that can be used to describe energy systems. First, the terms energy grid and energy system are established. Then, further relevant definitions of security in energy supply and grid and system supportability to describe energy grids and energy systems are given. These definitions were based primarily on German scientific publications. This is because Germany is seen as one of the leaders of the global energy transition, and a possible application reference of this paper involves Germany and the German legal framework for the energy sector.

Another more far-reaching challenge in the description of energy systems is the measurement and comparability of their properties. Relevant characteristics for describing energy systems are difficult to quantify.

One possibility to address this problem is the usage of so-called key performance indicators (KPIs). These key figures translate generic terms into concrete and measurable numbers and were initially used in the field of economics and business management to ensure effective and number-based corporate decisions [2] (pp. 27–29).

However, KPIs are also being used in the context of the energy sector and enable the comparison of different energy systems on the basis of numerical values. Based on the established definitions, for instance, KPIs can be determined to measure these specified energy system properties. As an example, KPIs are utilized in the publication by Efkarpidis et al. [3] in the context of the energy industry and the energy transition. Here, a KPI framework is developed and applied to obtain quantifiable and easily recognizable results if smart energy management systems are implemented [3] (pp. 3–4).

Also, the current System Stability Report published by the Federal Ministry for Economic Affairs and Climate Action (*German: Bundesministerium für Wirtschaft und Klimaschutz "BMWK"*) from November 2023 outlined that the increasing decentralization of the energy system in the course of the energy transition makes it necessary to reliably identify critical grid situations, potentially by using suitable indicators. The usage of KPIs for the measurable definition of technical terms is also discussed in this document [4] (p. 56).

Expanding on these current examples of the application of KPIs in the energy sector, in this paper, our own KPIs are developed to measure and quantify grid and system supportability. This will allow systems, installations and operating modes of plants to become comparable with regard to these criteria.

In order to identify possible concrete cases of application for the developed KPIs, the legal regulation of the energy industry in Germany is finally considered. Here, it becomes evident that the measurability of energy systems is becoming increasingly relevant for different legal mechanisms.

One example of this is a position paper published by the Federal Network Agency (*German: Bundesnetzagentur "BNetzA"*) in December 2023. The paper defines a proposal for identifying grid operators that are significantly affected by the additional costs of the integration of new renewable energy generation plants. This term is used in Section 21 of the Energy Industry Act (*German: Energiewirtschaftsgesetz "EnWG"*). According to the BNetzA recommendation, this qualitative definition should be based on a quantitative KPI that is determined transparently using a defined calculation formula [5] (p. 6).

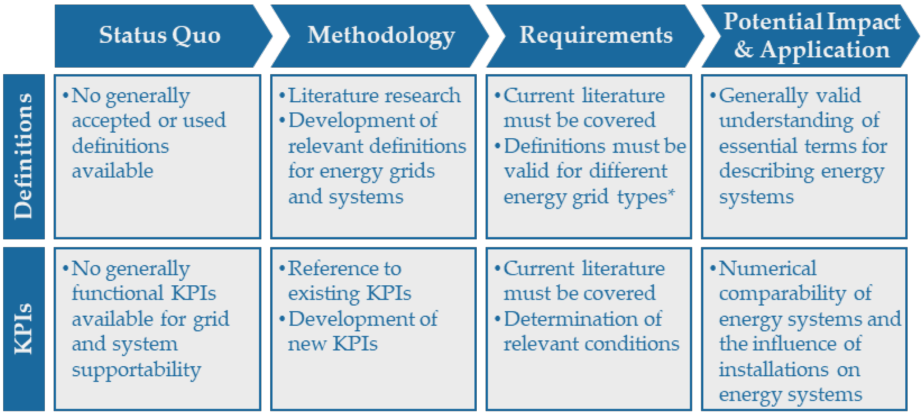
Although this example does not use a KPI that is in the direct thematic area of the ones that will be developed in this paper, it demonstrates that the principle of using numerical indicators to define qualitative terms can also be applied in the area of legal regulation.

However, there are also regulatory areas, for instance, with regard to certain auction mechanisms for innovative hydrogen installations that are put out to tender in accordance with the Renewable Energy Sources Act 2023 (*German: Erneuerbare Energien Gesetz 2023 "EEG 2023"*) that should link to grid supportability conditions for which comparability must be ensured, using KPIs, for example.

In order to provide a holistic analysis of the aforementioned topics, this article is divided into two overarching sections. Firstly, the technical definitions of terms are provided and explained. Then, the subject area of KPIs is addressed, an overview of representative KPIs is given, and our own KPIs are developed and exemplarily applied. As an outlook, possible applications of the created KPI are also provided, particularly with regard to the legal framework of the energy sector in Germany.

2. Methodology of Developing Definitions and Key Performance Indicators for Energy Systems

The structure of this paper for the development of definitions and KPIs is shown in Figure 1. A problem has been identified in that there is potential for optimization in the uniform use of definitions in the area of energy supply. There is also no consistent understanding in the area of grid and system supportability, which is why different terms and definitions, as well as no common and standardized KPIs, are used here. Due to the current political and social situation, there is great interest and necessity for improvement in this area, which is why this topic is being worked on intensively. This paper therefore begins with a comprehensive analysis of standardized definitions and KPIs in the energy sector.



	Status Quo	Methodology	Requirements	Potential Impact & Application
Definitions	• No generally accepted or used definitions available	• Literature research • Development of relevant definitions for energy grids and systems	• Current literature must be covered • Definitions must be valid for different energy grid types*	• Generally valid understanding of essential terms for describing energy systems
KPIs	• No generally functional KPIs available for grid and system supportability	• Reference to existing KPIs • Development of new KPIs	• Current literature must be covered • Determination of relevant conditions	• Numerical comparability of energy systems and the influence of installations on energy systems

* Electricity grids, gas grids and heat grids are considered in this paper.

Figure 1. Procedure and structure of this paper.

In conjunction with the extensive inventory analysis and literature research, our own definitions were then created and some existing definitions were partially adopted. Among other things, the focus here was on the general validity of the use of the terms for different grid types. In addition, several grids or systems with equal or higher priority are not considered. In this example, there is therefore one system consisting of three grids. This paper refers to electricity, gas and heat grids—but in general, other grids should also be covered. The definitions were used to create a standardized understanding of the most important terms in the energy sector.

A literature search was also conducted for KPIs. It should be noted that it is not possible to provide a complete or exhaustive list of KPIs. The KPIs listed in this paper are rather a brief insight into relevant KPIs. New KPIs are also to be created to quantify previously uncovered areas. These KPIs ensure, among other things, an evaluation of a grid expansion action or a comparison between different technical actions.

3. Results

3.1. Formulation of the Definitions for Energy Systems

As described in [6] (pp. 2–3), there are many different definitions of the terms used here in the literature. Some terms have been redefined or summarized from existing sources in order to provide a uniform view for the upcoming chapters.

Defining the terms *energy grid* and *energy system* is a crucial initial step when discussing further terms or concepts regarding the *security of energy supply*, *grid supportability* and *system supportability*. These definitions provide the basis for a clear and consistent understanding for the next chapters.

An *energy grid* defines a technical infrastructure for the grid-bound distribution of a tradable product (e.g., electricity, gaseous energy sources, heat) bound to specific technical, legal and economic framework conditions. Various installations are connected to an energy grid, which act as generators, storages, loads, converters or other energy installations. An energy grid can have several grid levels that differ in at least one significant feature (e.g., voltage, temperature, pressure).

An *energy system* comprises one or more energy grids, including all cross-grid installations (sector coupling).

The holistic approach of an energy system includes electricity grids as well as different gas and heat grids. However, it is important to underline that there is no consideration of several equal or superordinate energy systems. Once these basic terms have been defined, it is possible to move on to more specific concepts such as *security of energy supply*, *grid supportability* and *system supportability*.

3.1.1. Security of Energy Supply

In order to go into more detail on areas such as grid and system supportability, it is important to create a common understanding of terms such as the security of energy supply, as these terms are closely related. Of course, the security of energy supply must not suffer as a result of improving grid or system supportability. Aspects relevant to the security of energy supply are also an important factor when describing grid and system supportability.

Security of energy supply is the demand-based and affordable supply of tradable products in the energy sector in sufficient quantities at any given time. It is divided into short-term and long-term security of energy supply. The short-term security of energy supply includes operational aspects that ensure the quality of supply. The long-term security of energy supply includes the strategic aspects of the grid infrastructure, primary energy, load and generator structure and the energy policy framework [7] (pp. 205–206).

Figure 2 shows the relationship between the above terms. The individual terms here are defined as follows:

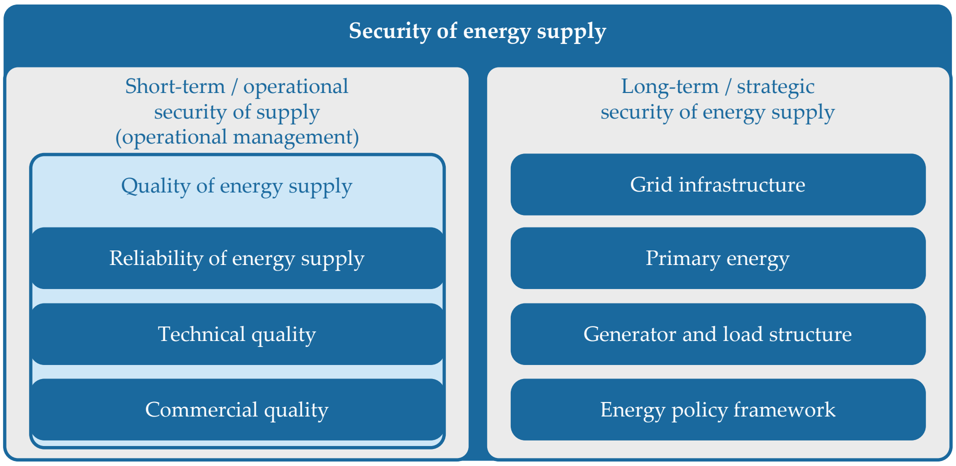


Figure 2. Security of energy supply.

The *quality of energy supply* considers technical and non-technical aspects of the short-term security of energy supply. It consists of the reliability of supply, the quality of the tradable product in the energy sector and the commercial quality [8].

Reliability of energy supply describes the demand-based supply under specified conditions over a specific time. Planned (e.g., maintenance, servicing) and unplanned (e.g., operational and weather-related faults) interruptions affect the reliability of energy supply [7] (pp. 207–208), [9] (pp. 3–5).

The *technical quality* of the tradable product describes its qualitative usability, considering technical guidelines and standards.

The *commercial quality* of the tradable product describes the quality of all transactions (e.g., the establishment of contractual relationships) between an energy supply company

(ESC) and a customer in an existing market. Elementary subject areas of commercial quality are data protection and IT security [7] (p. 202).

Grid infrastructure refers to the physical and organizational structure required to transport, for example, electricity or gas from generation to distribution and provide it to end consumers. This includes many different components such as lines, transformers, substations and other devices required to operate a reliable energy supply system.

Primary energy is the usable energy content of a naturally available energy source. Primary energy sources are energy sources that have not yet been converted—for example, wind power, solar energy, geothermal energy, brown coal, crude oil and natural gas [10].

The terms *generator* and *load structure* refer to the distribution and composition of energy producers and consumers. Among other things, the type and location of the respective producers and consumers are important factors here.

The *energy policy framework* includes all legal, regulatory and political requirements that affect the energy sector. This framework defines the basis for energy generation, distribution and consumption and is intended, for example, to benefit environmental protection and economic efficiency in addition to security of energy supply.

3.1.2. Grid and System Supportability

The concepts and relationships between *grid compatibility*, *grid supportability* and *system supportability* are an important part of this work. It is crucial to delineate and clearly define how the terms are used.

Grid compatibility is the fundamental prerequisite and minimum requirement of an installation that is connected to an energy grid. This ensures that an installation fulfills the technical and regulatory parameters required to be connected to the grid ([1] (p. 2), [6] (p. 2)).

Grid-supportive are single or multiple installations (generators, consumers or storage) which can offer services to the energy grid beyond the minimum requirements (grid compatibility). This can be achieved by knowledge, plannability or controllability of the installations by the grid operator and/or a contribution to maintaining the balance between generation and consumption. For this purpose, context-dependent operational management is necessary, depending on the grid situation. Furthermore, no additional grid expansion may be caused in the same or other grid levels [6] (p. 5).

System-supportive are single or multiple installations which can provide system services to the energy system and/or parts of the energy system beyond the minimum requirements of grid compatibility in all affected energy grids. This can be achieved by knowledge, plannability or controllability of the installations by the grid operator and/or through appropriate operational management.

Figure 3 shows the relation between the terms just introduced. Grid compatibility must be fulfilled at all times. An installation can operate grid support in several grids and therefore be considered to be system-supportive. However, it is also possible for an installation to be grid-supportive in one grid but not have a positive impact on the second grid. In this case, the installation would be grid-supportive but not system-supportive. The conclusion, therefore, is that grid supportability and system supportability can overlap, but do not have to.

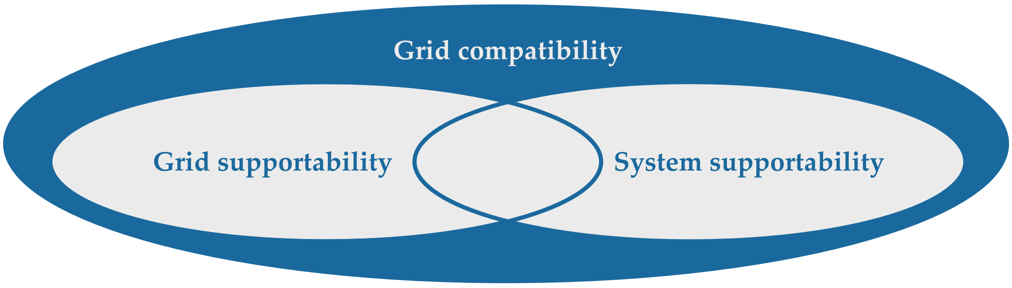


Figure 3. Relation of grid compatibility and grid and system supportability. Source: own representation according to [6].

3.2. Key Performance Indicators for Energy Systems

3.2.1. Overview of Existing Standards

In the extensive world of energy supply, there is a large number of existing KPIs that serve to quantify and make measurable various topics such as security of energy supply, economy or commercial and technical quality.

It is important to point out that the following list is not exhaustive. It is merely a small preselection of relevant KPIs and can be assigned to some analyzed areas. This overview provides an insight into the categories and highlights the significance and application of some KPIs. Further examples and more comprehensive lists of KPIs can be found in [11,12] or [13]. In addition to some technical KPIs, many economic indicators can also be found here. Other important key figures are often defined by standards or laws.

The first three KPIs in Table 1 are important and frequently used indicators for assessing the security of energy supply. The SAIDI index is calculated by dividing the sum of all supply interruptions by the total number of consumers. It therefore describes the average value of supply interruptions in a grid per consumer supplied [14]. The SAIFI index indicates how often a connected customer is affected by an outage within a specified period of time [14], and the ASIDI index indicates the average supply interruption per connected rated load within a specified period of time (often one calendar year) [15].

Table 1. Small selection of existing KPIs.

Term	Assigned Topic	Sector
System Average Interruption Duration Index (SAIDI)	Security of Energy Supply	-
System Average Interruption Frequency Index (SAIFI)	Security of Energy Supply	-
Average System Interruption Duration Index (ASIDI)	Security of Energy Supply	-
Wobbe Index	Technical Quality	Gas
Flicker	Technical Quality	Electricity
Overall Equipment Effectiveness (OEE)	Generator and Load Structure	-
Levelized cost of electricity (LCOE)	Commercial Quality	-
Share of grid fees, levies, etc., in total costs	Energy Policy Framework	-

The Wobbe Index is a KPI defined in DIN EN ISO 15971 that describes the quality of fuel gases. It is therefore assigned to the commercial quality category [16].

In the electricity sector, many key figures are specified by standards or legislation. DIN EN 50160, "Voltage characteristics of electricity supplied by public electricity networks", describes some key figures for the electricity grid. In addition to flicker, this also includes other characteristics such as waveforms, symmetries of the phase-to-phase voltages and frequency [17].

The OEE is a widely used standard for measuring manufacturing productivity. It measures the time in which a system or production line is productive. Therefore, 100% productivity means that a production line only produces good parts as quickly as possible and without downtime. This also assumes that quality, speed and availability are all at 100%. This KPI was originally intended for the evaluation of production or manufacturing plants. Due to the parameters that can also be applied to energy generation plants (quality, performance and availability), it should also be possible to apply the KPI here [18].

The calculation of the LCOE enables a comparison of power plants with different generation and cost structures and is therefore a KPI in the commercial quality category. However, this evaluation method can also be adapted to determine the energy production costs and thus include other energy sources [19].

The share of grid fees, levies, etc., in the total costs of energy generation is an energy policy KPI that makes the composition of the energy production costs more transparent and thus shows what proportion of the costs is politically determined.

As it can be seen from the table above, there is a need to catch up in the area of grid and system supportability. There have been few KPIs in this topical area to date, but a quantitative assessment of these areas is particularly in demand and necessary.

The following chapters of this paper deal with the creation of two novel KPIs that are used to quantitatively evaluate the grid and system supportability or to compare two different grids.

3.2.2. Determination of Key Performance Indicators for Energy Systems

The search for a standardized KPI for assessing the grid or system supportability of different grids (e.g., electricity, heat, gas) is a challenge, as the fundamental parameters that characterize the operation of the grids vary depending on the energy source and grid type. This chapter analyzes the elementary parameters in the electricity, gas and heat grid, highlights the spatio-temporal dependency and presents the KPIs created and the adaptability of the formulas.

The terms grid and system supportability were introduced in Section 3.1.2. Here, it is described that grid supportability is the provision of services that go beyond the minimum requirements to ensure the balance between generation and consumption. This service can, for example, be an intelligent operating mode that results in an improvement in the voltage or frequency curve. A plant is therefore grid-supportive or operating in a grid-supportive manner if it has a positive effect on the voltage curve of a grid, which, in our example in Figure 4, means the improvement of the parameter towards 1 pu.

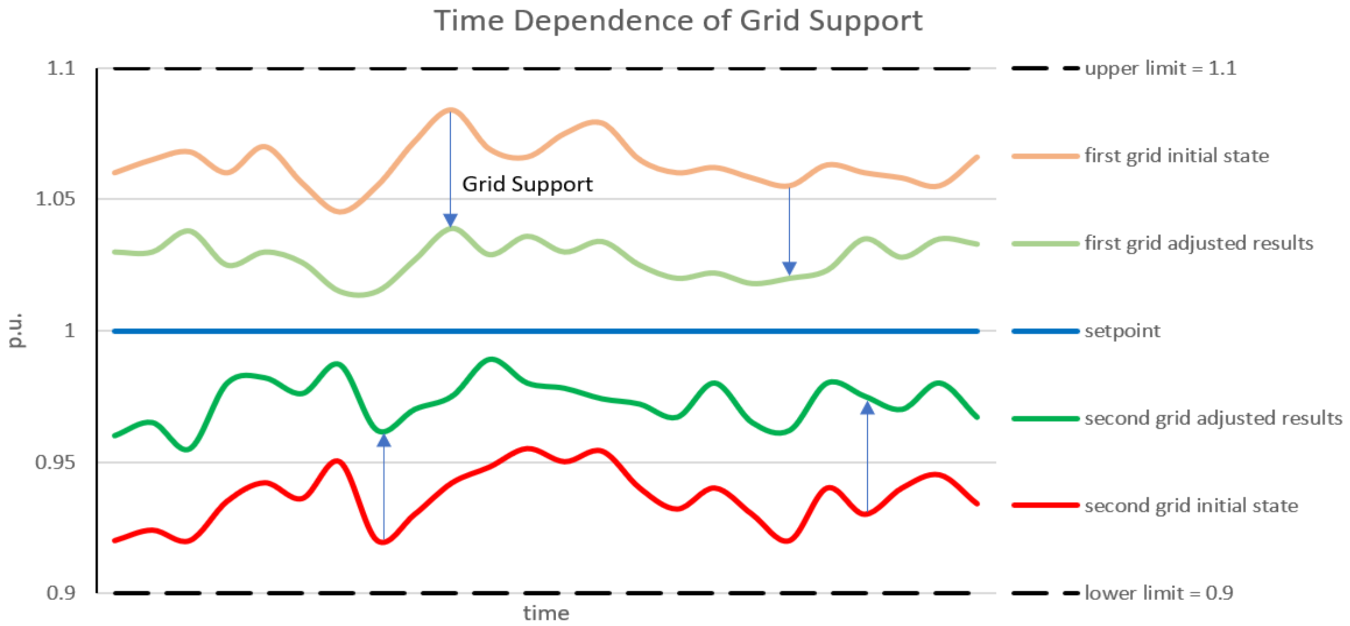


Figure 4. Potential curve of voltage in an electricity grid.

The elementary parameters of the operations are simplified in the first approach. However, the parameters considered can then be easily expanded. Voltage and frequency are taken into consideration for the electricity grid, pressure for the gas grid and temperature for the heat grid.

Figure 4 shows a potential curve of voltage in an electricity grid. The auxiliary unit of measurements per unit (pu) is used for the y axis in order to create general validity for different grids and measured parameters. For this purpose, the exact measured value is divided by a reference value, and a dimensionless and standardized value is obtained. This allows us to compare different grids and to consider several fundamental parameters, such as voltage and frequency, for the electricity grid. After evaluating the individual grid supportability of different grids, the system supportability of an entire system can also be evaluated and the interdependencies can be visualized. This applies, in particular, to plants that operate in more than one grid, such as an electrolyzer (electricity and gas) or a heat pump (electricity and heat).

The target set value is always 1.00 pu. The actual deviation upwards and downwards should be kept as low as possible. Actions that improve these values increase the grid supportability of the respective grid. The limit values (here, 0.9 pu and 1.1 pu) are to be defined by the user (but they can also be defined by law or technical regulation) and are only examples. These values must not be exceeded or fallen short by actions. The temporal basis of this curve can also be defined by the user and can, for example, be one year. However, a representative period should be selected.

In order to consider the location dependency in addition to the time-dependent consideration, several measurements are taken at different locations in the grid. This produces x diagrams similar to Figure 4 for x measurements in the grid.

To express and evaluate this difference using a formula, the individual deviations are totaled (set value: "SV"; actual value: "AV") and then divided by the set value. This is then divided by the number of measurements (T) and measuring points (X), which is why both the measuring interval and the number of measuring points in the grid are irrelevant. The number and location of the measuring points as well as the time span and frequency of the measurements can be freely selected and depend on the intention of the operator or the framework conditions of the action. The initiator of the technical action usually specifies the number and locations of the metering points to be selected.

However, it is important to ensure that meaningful values and locations are selected and documented in order to create a reproducible and comparable value for the Grid Support Indicator (GSI). Relevant locations can include special grid connection points or other significant places in the grid (e.g., busbars in electricity grids) that are particularly affected by the intended action. However, only one higher-level measuring point can be selected to evaluate the influence. Therefore, the number and positioning of the measuring points always depend on the respective project and cannot be determined across the board. It must also be ensured that the different measurements are precisely synchronized in time due to the high influence of small deviations. This is necessary in terms of measurement technology anyway, especially in the area of electrical grids, and corresponds to the state of the art as described in [20] (235 et seqq.).

$$GSI = \left(\sum_{x=1}^{X} \sum_{t=1}^{T} \frac{|SV(x,t) - AV(x,t)|}{SV(x,t)} \right) \times \frac{1}{T} \times \frac{1}{X}, \qquad x,t \geq 1, \forall x,t \in \mathbb{R} \tag{1}$$

As deviations from the set value should be minimized, a lower *GSI* value is better. The target value of the KPI is therefore an optimization towards 0. The *GSI* must be calculated for each relevant parameter in the grid. In the electricity grid example, the *GSI* must therefore be calculated for the voltage and frequency. Pre-factors (f) are used to weigh and standardize the individual GSI values. Generally speaking, the GSI for any grid (X) with the relevant parameters $a, b, \ldots, n$ is then

$$GSI_X = f_{X,a} \times GSI_{X,a} + f_{X,b} \times GSI_{X,b} + \cdots + f_{X,n} \times GSI_{X,n} \tag{2}$$

The formula for the electricity grid example with the relevant parameters of voltage (U) and frequency (f), including pre-factors, is as follows:

$$GSI_{electricity} = f_{electricity,\ U} \times GSI_{electricity,\ U} + f_{electricity,\ f} \times GSI_{electricity,\ f} \tag{3}$$

The pre-factor for several relevant parameters is made up of a normalization factor (N) and a weighting factor (W).

$$f_{X,\ a} = f_{X,a,\ N} \times f_{X,\ a,W} \tag{4}$$

The normalization factor normalizes different deviations in relation to the permissible limit values. The influence of deviations with higher permissible limit values is weakened, while the influence of deviations with lower permissible limit values is increased. The first relevant parameter considered in grid *X* is used here as a reference, which is why the normalization factor for the first relevant parameter is always 1. The choice of the first relevant parameter of a grid affects the final value of the *GSI*. Careful documentation of the framework conditions and parameters used as well as the use of the *GSI* as a comparative value must therefore be ensured. The absolute values of the KPI are often less meaningful, which is why the KPI should only be used for comparison purposes (e.g., the *GSI* of two different grids with the same framework conditions or comparison of a grid before and after an expansion or modification action).

$$f_{X,a,N} = \frac{f_{X,a,limit}}{f_{X,a,limit}} \tag{5}$$

$$f_{X,a,limit} = f_{X,a,upper\_limit} - f_{X,a,lower\_limit} \tag{6}$$

A normalization factor is now also determined for further parameters, *b* and *n*, which are set in relation to the reference value:

$$f_{X,b} = f_{X,b,N} \times f_{X,b,W} \tag{7}$$

$$f_{X,b,N} = \frac{f_{X,a,limit}}{f_{X,b,limit}} \tag{8}$$

$$f_{X,b,limit} = f_{X,b,upper\_limit} - f_{X,b,lower\_limit} \tag{9}$$

$$f_{X,n} = f_{X,n,N} \times f_{X,n,W} \tag{10}$$

$$f_{X,n,N} = \frac{f_{X,a,limit}}{f_{X,n,limit}} \tag{11}$$

$$f_{X,n,limit} = f_{X,n,upper\_limit} - f_{X,n,lower\_limit} \tag{12}$$

Once the normalization factors have been determined and the deviations of the set values are normalized in the *GSI*, weighting factors are required to finally determine the pre-factor, *f*. Weighting factors are defined by the user and allow the individual relevant parameters to be weighted or prioritized to varying degrees. The sum of all individual weighting factors must always be 1.

$$f_{X,a,W} + f_{X,b,W} + \cdots + f_{X,n,W} = 1 \tag{13}$$

In the electricity grid, the pre-factors for the two relevant parameters, *U* and *f*, are determined as follows:

$$f_{electricity,U} = f_{electricity,U,N} \times f_{electricity,U,W} \tag{14}$$

$$f_{electricity,U,N} = \frac{f_{electricity,U,limit}}{f_{electricity,U,limit}} \tag{15}$$

$$f_{electricity,U,limit} = f_{electricity,U,upper\_limit} - f_{electricity,U,lower\_limit} \tag{16}$$

$$f_{electricity,f} = f_{electricity,f,N} \times f_{electricity,f,W} \tag{17}$$

$$f_{electricity,f,N} = \frac{f_{electricity,U,limit}}{f_{electricity,f,limit}} \tag{18}$$

$$f_{electricity,f,limit} = f_{electricity,f,upper\_limit} - f_{electricity,f,lower\_limit} \tag{19}$$

$$f_{electricity,U,W} + f_{electricity,f,W} = 1 \tag{20}$$

In the other two grids (gas and heat), there is only one relevant parameter considered, which is why no weighting or normalization is required here. If other relevant parameters are to be included, the formulas can be extended as in the electricity grid example. For the gas and heat grid with one relevant parameter, Formula (1) can be used.

If an entire energy system is considered, the GSIs specified above for the individual grids in the system are required first. The System Supportability Indicator (*SSI*) can now be calculated with the help of normalization and weighting factors. The pre-factors are calculated in a similar way to the *GSI*.

$$SSI = f_{electricity} \times GSI_{electricity} + f_{gas} \times GSI_{gas} + f_{heat} \times GSI_{heat} \tag{21}$$

$$f_{electricity} = f_{electricity,N} \times f_{electricity,W} \tag{22}$$

$$f_{gas} = f_{gas,N} \times f_{gas,W} \tag{23}$$

$$f_{heat} = f_{heat,N} \times f_{heat,W} \tag{24}$$

If there is more than one relevant parameter in the grid, the mean value of the permissible deviation of the grid must be calculated before the *SSI* is calculated so that the different parameters of the various grids have an equal impact on the change in the KPI. Here, the individual limits are added together for the electricity grid and then divided by the number of relevant parameters (n) in the grid. For the two grids with only one relevant parameter, the range of permissible values simply applies. This results in the following for the three different grids:

$$f_{electricity,limit} = \frac{\left|\left(f_{electricity,U,upper\_limit} - f_{electricity,U,lower\_limit}\right)\right| + \left|\left(f_{electricity,f,upper\_limit} - f_{electricity,f,lower\_limit}\right)\right|}{n} \tag{25}$$

$$f_{gas,limit} = f_{gas,p,upper\_limit} - f_{gas,p,lower\_limit} \tag{26}$$

$$f_{heat,limit} = f_{heat,\theta,upper\_limit} - f_{heat,\theta,lower\_limit} \tag{27}$$

The grids are then placed in relation to each other again, with the electricity grid again being assigned the normalization factor 1 as the reference grid.

$$f_{electricity,N} = \frac{f_{electricity,limit}}{f_{electricity,limit}} \tag{28}$$

$$f_{gas,N} = \frac{f_{electricity,limit}}{f_{gas,limit}} \tag{29}$$

$$f_{heat,N} = \frac{f_{electricity,limit}}{f_{heat,limit}} \tag{30}$$

As with the *GSI*, the weighting factor can be determined by the user and thus contains its own prioritization of the individual grids. Once again, the sum of all individual weighting factors must equal 1.

$$f_{electricity,W} + f_{gas,W} + f_{heat,W} = 1 \tag{31}$$

A relevant use case could be the assessment of a grid expansion action. In this case, an *SSI* would be calculated for the initial state and another *SSI* for the state after the action. The grid expansion could then be quantitatively evaluated using the KPIs presented. A

ΔSSI could then be specified in absolute or relative terms. This would make it easy and effective to compare and evaluate different grid expansion actions.

$$\Delta SSI_{abs} = SSI_{before} - SSI_{after} \tag{32}$$

$$\Delta SSI_{rel} = \frac{SSI_{before} - SSI_{after}}{SSI_{before}} \tag{33}$$

3.2.3. Exemplary Usage of the Key Performance Indicators for Heat Pumps

The KPIs that have just been introduced will be used as examples in this chapter to demonstrate the precise use, strengths and weaknesses of the new evaluation option. These KPIs not only provide a quantitative assessment, but also enable an in-depth analysis of grid and system supportability. This application shows how these KPIs can help to effectively assess the performance of grids and systems and derive targeted actions for optimization.

For the exemplary sample calculation, data are required to calculate the newly created KPIs. For this purpose, both real data from the teaching and exhibition building of the FH Westküste (*German: Lehr- und Ausstellungsgebäude "LAG"*) and simulated data using PowerFactory 2023 (PowerFactory is a leading grid calculation software for the calculation of generation, transmission, distribution and industrial grids [21]) software were used.

Figure 5 illustrates the structure of the electricity grid simulated in PowerFactory. A high-voltage grid with a voltage of 110 kV is shown. The high-voltage busbar can be seen directly below. Between this and the medium-voltage busbar is a 25 MVA transformer, which transforms the 110 kV high voltage to a 20 kV medium voltage. Two medium-voltage busbars are then connected to the medium voltage, each of which has an identical residential area with 30 residential units as a load. The left-hand busbar has an electrical load of 105 MWhel and a heat pump with a load of 143 MWhel for a potential heat grid. The right-hand busbar has identical loads, but is also fed by an installed photovoltaic (PV) plant with a power of 5 MW. The medium-voltage line is assumed to be 10 km long. Table 2 shows an overview of the parameters used. Two different systems are therefore considered, consisting of an electricity and heat grid, with the second system having a PV plant.

Table 2. Parameters used for the simulation in PowerFactory.

Description	Value
HV-System	110 kV
HV/MV-Transformer	25 MVA
MV-System	20 kV
MV-Cable	10 km NA2XS(F)2Y 150 mm^2
Number of households	30
Electrical annual consumption (rural area)	105 MWh$_{el}$
Electrical annual consumption (heat pumps)	143 MWh$_{el}$
Rated power of open space PV facility	5 MW

The electrical load of the heat pump and the outdoor temperature curve are shown in Figure 6. These are real values from the LAG of the FH Westküste. With the help of these data and the corresponding internal temperatures, the GSI_{heat} could be easily calculated later on. In addition, the data from the LAG serve as the basis for the heating loads of the PowerFactory simulation. The electrical load of the heat pump and the outdoor temperature curve are shown in Figure 6. These are real values from the LAG of the FH Westküste. With the help of these data and the corresponding internal temperatures, the GSI_{heat} could be easily calculated later on. In addition, the data from the LAG serve as the basis for the heating loads of the PowerFactory simulation.

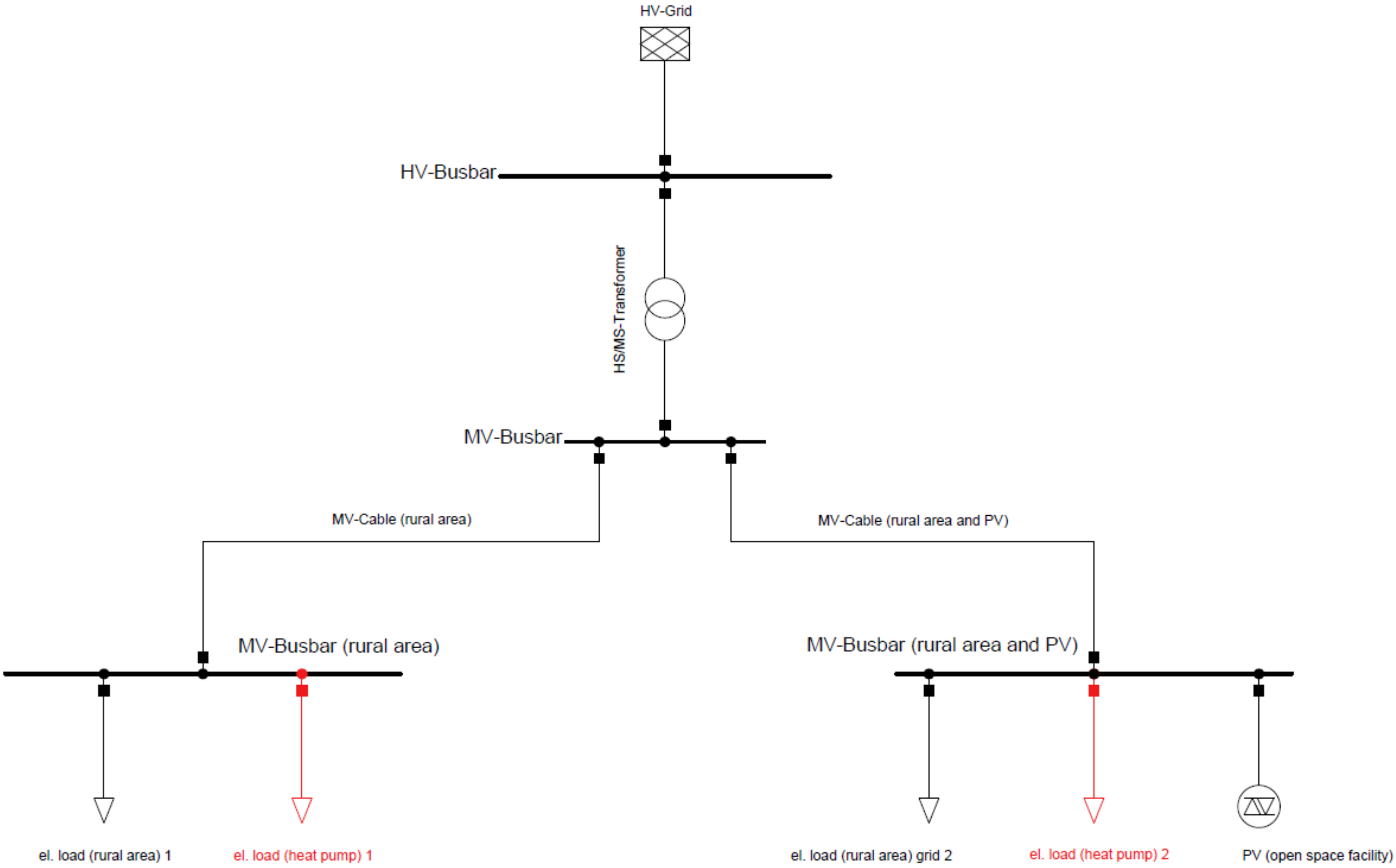


Figure 5. Structure of the simulated grids in PowerFactory.

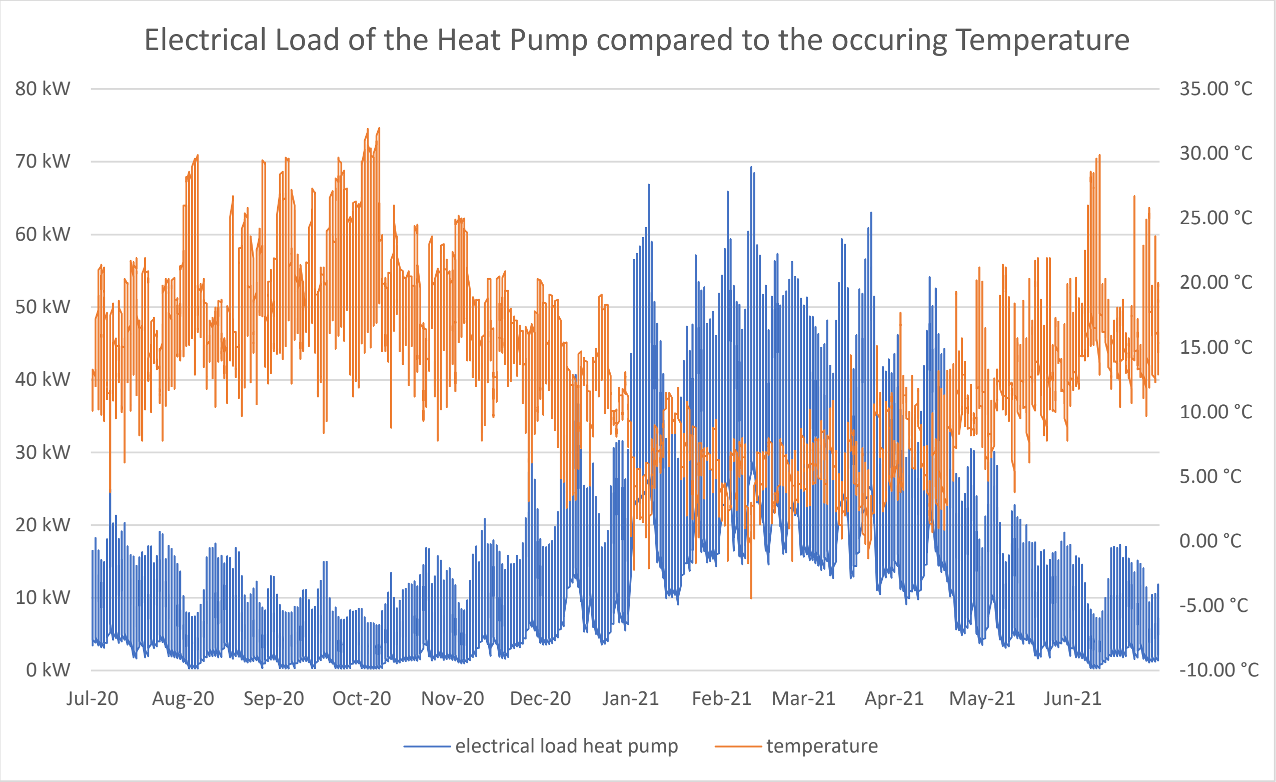


Figure 6. Electrical load of the heat pump compared to the occurring temperature.

A standard load profile (SLP: residual load h0) was selected for the electrical load of the residential area. Figure 7 shows the daily pattern for weekdays, Saturdays and Sundays for these profiles in the summer. There are also different courses for winter and spring/autumn.

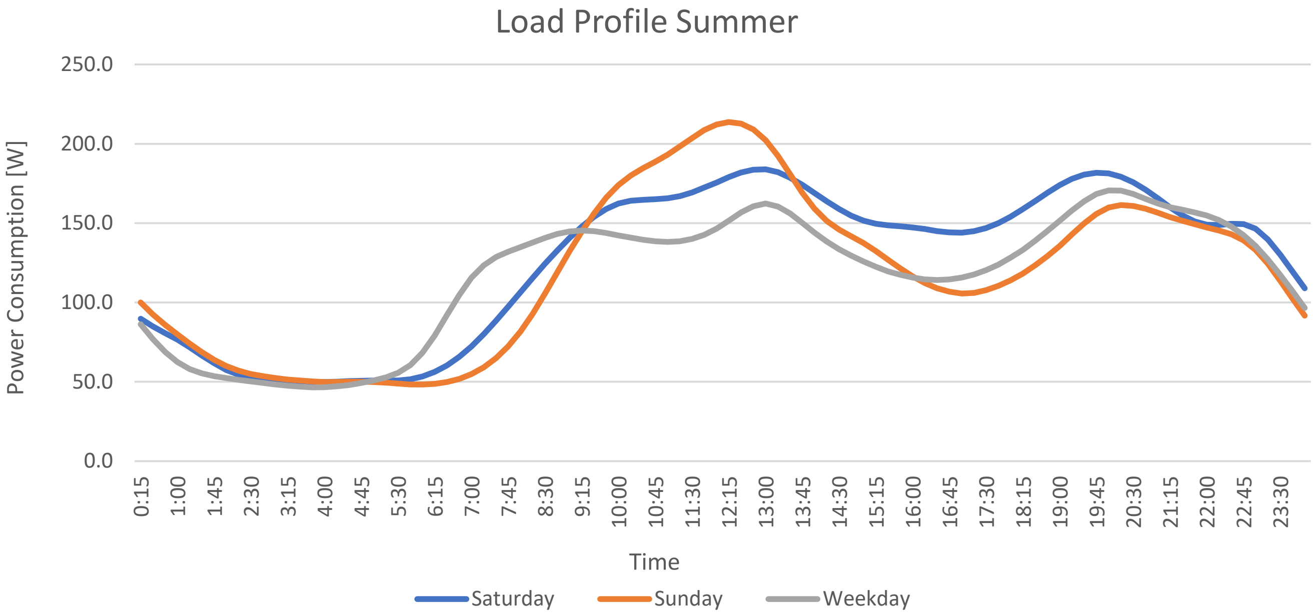


Figure 7. Daily curve of the electrical load in the summer.

The electricity production of the PV plant was designed according to the PV production (Figure 8) in 2020/2021 for the whole of Germany [22]. These exemplary values were selected to carry out the sample calculation. Of course, in a real application, the actual measured values should always be selected and not average values or sample values.

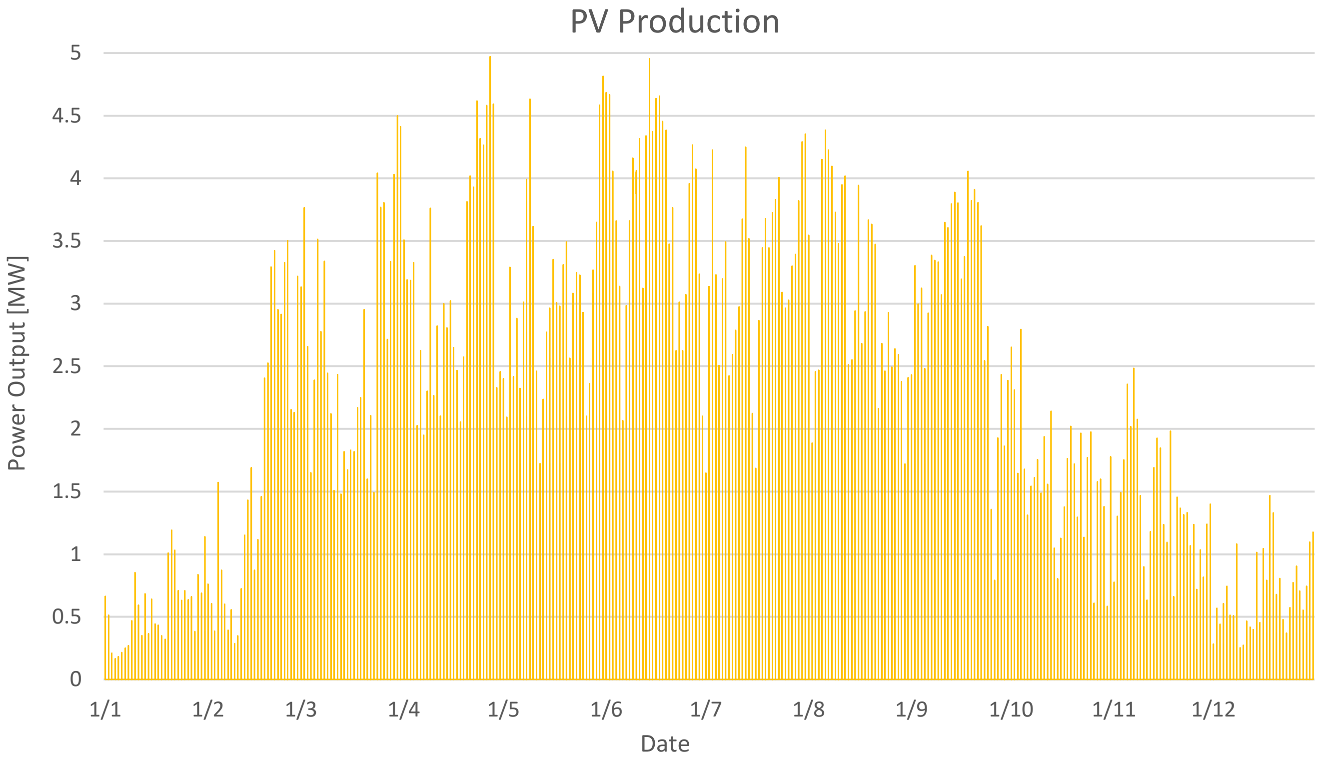


Figure 8. PV production.

The initial situation for the simulation is the operation without a heat pump (fossil operation). In addition, there are various scenarios for the two grids as to how a heat pump could be integrated. In this case, the initial situation is compared with the operating modes shown in Figure 9: day-time operation, night-time operation and demand-driven operation.

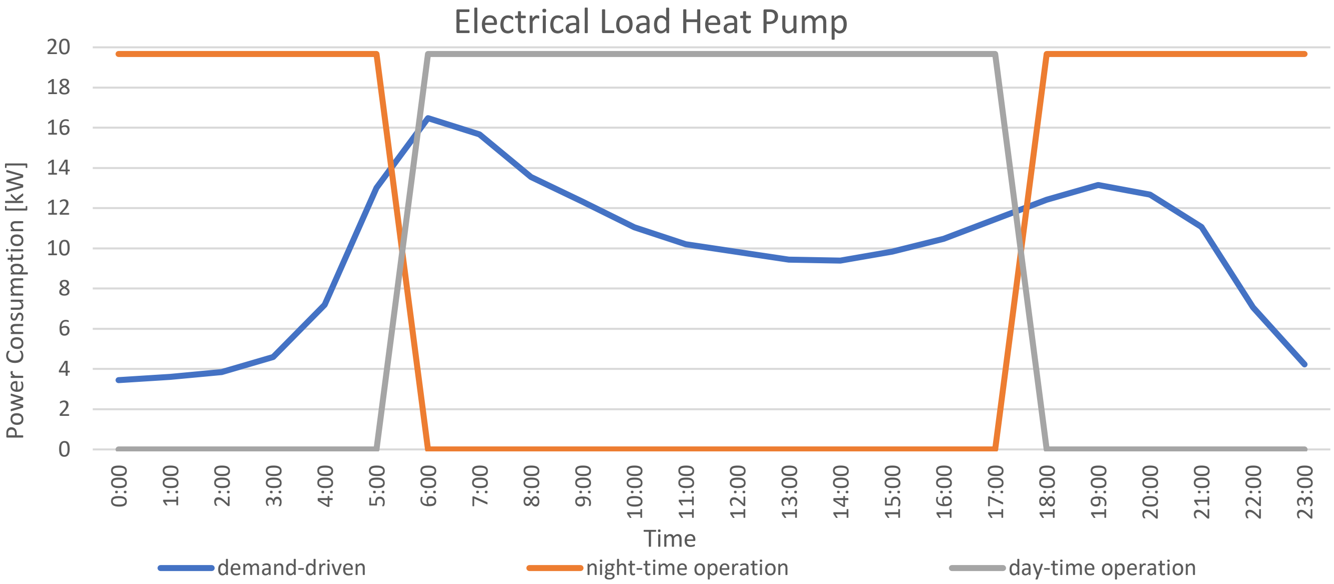


Figure 9. Exemplary course of the operating modes considered.

The following values for the *GSI* shown in Table 3 can then be calculated using the simulation scenarios listed and the formulas introduced in Section 3.2.2. As only the voltage and not the frequency is considered as a relevant parameter in the power grid in this simplified example, no pre-factors are necessary for the calculation of the *GSI* and it can be calculated using the deviations from the set value.

Table 3. Absolute GSI values for the electricity grid.

Scenario	MV-Busbar	MV-Busbar (Rural Area)	MV-Busbar (Rural Area and PV)
$GSI_{electricity,U,base\text{-}scenario}$	0.00390923	0.01127173	0.00789233
$GSI_{electricity,U,demand\text{-}driven,grid\_1}$	0.00391068	0.01136230	0.00789530
$GSI_{electricity,U,night\text{-}time\_operation,grid\_1}$	0.00391168	0.01136269	0.00789504
$GSI_{electricity,U,day\text{-}time\_operation,grid\_1}$	0.00391153	0.01136276	0.00789532
$GSI_{electricity,U,demand\text{-}driven,grid\_2}$	0.00391065	0.01127468	0.00798282
$GSI_{electricity,U,night\text{-}time\_operation,grid\_2}$	0.00391080	0.01127360	0.00797711
$GSI_{electricity,U,day\text{-}time\_operation,grid\_2}$	0.00391104	0.01127425	0.00798004

The following GSIs shown in Table 4 can be calculated for the heat grid using the data from the LAG. The demand-driven operating mode performs best here, as the heat output is generated almost simultaneously. This mode of operation is positive in the heat grid, but can have a negative effect on the electricity grid, as peak loads occur and cannot be reduced or absorbed by continuous heat generation. It is followed by day-time operation, as most of the load occurs during the day, and finally, night-time operation.

Table 4. GSI of the heat grid.

Description	Value
$GSI_{heat,demand\text{-}driven}$	0.000000
$GSI_{heat,day\text{-}time\_operation}$	0.007216
$GSI_{heat,night\text{-}time\_operation}$	0.011227

Table 5 shows the framework conditions of the simulation with the limit values for calculating the pre-factors for the SSI. Set values for the individual grids are derived from standards or defined by operators. The weighting factors were determined by us. The missing parameters for calculating the SSI are then determined using the data and formulas introduced earlier:

$$SSI = f_{electricity} \times GSI_{electricity} + f_{gas} \times GSI_{gas} + f_{heat} \times GSI_{heat} \tag{21}$$

$$f_{electricity} = f_{electricity,N} \times f_{electricity,W} \tag{22}$$

$$f_{electricity,limit} = f_{electricity,U,upper\_limit} - f_{electricity,U,lower\_limit} = 0.2 \tag{25}$$

$$f_{electricity,N} = \frac{f_{electricity,limit}}{f_{electricity,limit}} = 1 \tag{28}$$

$$f_{electricity} = f_{electricity,N} \times f_{electricity,W} = 0.75 \tag{22}$$

$$f_{heat} = f_{heat,N} \times f_{heat,W} \tag{24}$$

$$f_{heat,limit} = f_{heat,\theta,upper\_limit} - f_{heat,\theta,lower\_limit} = 0.15 \tag{27}$$

$$f_{heat,N} = \frac{f_{electricity,limit}}{f_{heat,limit}} = 1.3333 \tag{30}$$

$$f_{heat} = f_{heat,N} \times f_{heat,W} = 0.3333 \tag{24}$$

Table 5. Limit values and pre-factors calculated from them.

Description	Value
Target voltage value	20 kV
$f_{electricity,U,upper\_limit}$ (at 22 kV)	1.1
$f_{electricity,U,lower\_limit}$ (at 18 kV)	0.9
$f_{electricity,limit}$	0.2
$f_{electricity,N}$	1
$f_{electricityW}$	0.75
$f_{electricity}$	0.75
Target temperature value	60 °C
$f_{heat,\vartheta,upper\_limit}$	1.09
$f_{heat,\vartheta,lower\_limit}$	0.94
$f_{heat,limit}$	0.15
$f_{heat,N}$	1.3333
$f_{heat,W}$	0.25
f_{heat}	0.3333

In this calculation, it is noticeable that the influence of the deviations in the heat grid is theoretically increased due to the lower permissible limits, but is reduced overall due to the low weighting.

The calculated pre-factors can then be used to calculate and compare the *SSI* of individual scenarios using Formula (21), introduced earlier in Section 3.2.2, and the values from Table 5.

Table 6 clearly shows that the two systems achieve the best results in day-time operation. If several parameters are to be considered in the grids or an additional grid has to be implemented, the formulas can be extended as in Section 3.2.2. Additional pre-factors are then required.

Table 6. SSIs of the two different systems.

Description	Value
$SSI_{day\text{-}time\_operation,grid2}$	0.00579133
$SSI_{day\text{-}time\_operation,grid1}$	0.00579240
$SSI_{night\text{-}time\_operation,grid2}$	0.00819433
$SSI_{night\text{-}time\_operation,grid1}$	0.00819631
$SSI_{demand\text{-}driven,grid2}$	0.00953231
$SSI_{demand\text{-}driven,grid1}$	0.00953234

4. Discussion

This section will provide a brief critical discussion of the research results presented within this paper, focusing on the developed KPIs.

First, however, the formulated definitions for the terms used to describe energy systems are discussed. In this paper, these are formulated as a generally valid possibility for the characterization of energy systems. Nevertheless, it should be considered that this will probably not be implemented consistently in the scientific community and that different definitions will continue to be used to describe energy systems.

Second, the developed KPIs, the GSI and SSI, will now be discussed in focus. These are basically capable of indicating the grid and system supportability of plants, the operating modes of installations and whole energy systems. This can be shown in both the theoretical development of the two KPIs and also in the presented exemplary application scenario.

However, this method of quantifying grid and system supportability also has limitations and disadvantages which have to be considered.

At first, it should be pointed out, as already mentioned above, that the GSI and SSI are only of limited significance as stand-alone absolute indicators. The advantage of these KPIs is that they are very useful as comparative values, for example, for different installation projects or plant operating modes.

In addition, the freely selectable weighting factors and other framework conditions when calculating the KPIs have a major influence on the results. If certain modifications were made, there might be considerable deviations in the achieved results, which can lead to distortions in the conclusion of the calculation. It is therefore necessary to accurately document the selected weighting factors and all framework conditions relevant for the calculation. It is also useful to provide specifications regarding these values and conditions if different projects should be compared on the same basis. Alternatively, the framework conditions must be defined by appropriate instructions.

Another deficiency that appears with both developed KPIs is the small difference that occurs when comparing different calculated values. This applies equally to absolute and relative values of the KPIs. Therefore, a direct comparison in the first instance is difficult. One potential suggestion to improve this would be the introduction of an amplification factor that shifts the differences in the calculated values by several decimal powers so that the results can be recognized and displayed more readily.

In summary, there are certain deficits regarding the developed KPIs, but these can be compensated by appropriate actions. In conclusion, it can be stated that the objective of this paper, the development of calculable and measurable indicators for grid and system supportability, was achieved.

5. Outlook

After the development of the key performance indicators for grid and system supportability in the process of this paper, the question arises of potential fields of application of these

KPIs as well as possible subsequent scientific work that can be based on them and which research approaches can additionally be pursued. Therefore, the following section provides an outlook on these two areas of potential applications and further research opportunities.

An exemplary utilization of the KPIs has already been outlined in this paper, where the operating mode of a heat pump and its impact on the grid and system supportability were analyzed. Nevertheless, many other possible areas of application of the KPIs are conceivable, some of which are discussed below. In general, the main focus when using these KPIs should be on comparative analyses. This means that different states (e.g., operating modes, locations of installations, etc.) are considered in relation to each other (improvement of or reduction in grid and system supportability). This is significantly more expressive than simply looking at the absolute values of the KPIs.

Consequently, the first listed use case for the developed KPIs is also the comparison of different operating modes of installations that function either only in one grid or in a sector-coupling manner. These can be analyzed and benchmarked in terms of their impact on the energy grid or system using the KPIs, providing a transparent and comprehensible basis for the evaluation. In addition, this comparison cannot solely be made with different operating modes of plants, but also with different external intelligent plant operational controls of entire energy systems, which enables them to be assessed in terms of their grid and system supportability based on quantifiable parameters.

Another possible utilization of the KPIs is the evaluation of the impact of new types of installations on the energy system. As the energy transformation progresses, there will be a large-scale installment of various new types of plants in the energy system, for instance, electrolysis units for hydrogen production. These installations need to be effectively integrated into the electricity grid and also the entire energy system with regard to several technical and economic aspects.

One of the key factors here is the grid and system supportability, which is also addressed in current political documents such as the update of the National Hydrogen Strategy (*German: Fortschreibung der Nationalen Wasserstoffstrategie "NWS"*). This includes both the localization and the operational mode of the plants [23] (p. 6).

The developed KPIs could be used to provide numerical evidence of whether and how well these requirements have been implemented in realized projects. In addition, the KPIs also enable a comparison of different plant locations, for instance, within the electricity grid. This ensures that the electrolyzers are located in the most beneficial position for the grid.

An additional area that can be assessed using the KPIs is the evaluation of various possible investment alternatives within an energy system with regard to their potential impact on grid and system supportability. A concrete illustration here, following on from the example of the heat pump discussed in this paper, would be whether a larger heat storage tank or an additional heat pump should be added to a heating system in order to cover increasing demand. With the help of the developed KPIs, a technical view could be included in addition to the usual economic analysis.

The concluding element of the overview of possible fields of application for the KPIs concerns a legal thematic. Certain state subsidy mechanisms, which are used to provide financial support for politically intended installations in the energy system, can be linked to further technical conditions, such as grid and system supportability requirements.

Examples of this can be found in the EEG 2023. Paragraph 39n describes the subsidization of renewable energy plants in the form of innovation auctions, whereby installations that are particularly grid and system supportive should be subsidized. In order to evaluate which plants are grid or system supportive and how the further gradation caused by the word "especially" in the legal text can be made, a possible approach could be the utilization of the KPIs, since they also provide measurement and comparability by underpinning the specified terms with numerical values.

Another legal aspect in the EEG 2023 for the application of the developed KPIs can be identified in paragraph 88d. This regulation stipulates that a directive can be issued for innovation auctions in which, among other things, the basis for the selection of the auction bids can be concretized. This enables the decision to be made not only in accordance with the lowest-price bids, but also on the inclusion of an evaluation criterion that assesses the grid and system supportability of the proposed projects. The developed KPIs could provide such an evaluation criterion, which has to be comparable and transparently determined.

In the second section of the conclusion, two examples of possible further research opportunities that could be based on this paper will be described. In these areas, the KPIs can be used as a foundation, although there is still a need for academic work in order to fully examine the topics.

The first possible research field mentioned here is the development of an optimization software for energy systems that focuses on grid and system supportability. The usual energy optimization programs, some of which are already available on the market in form of so-called virtual power plants (VPPs), use economic parameters such as the profitability of individual plants to optimize their operating mode. A prospective new energy optimization software could therefore be designed to minimize the GSI or SSI within an energy grid or energy system through an appropriate installation control, which would accordingly increase the grid or system supportability. It may be necessary to adapt the calculation methodology of the KPIs to the structure of the developed optimization software, but their informative value should not be changed in this process. In addition, a conclusive comparison between the results of economically optimized VPPs and the optimization software with the developed KPIs regarding grid and system supportability can be made.

The second potential further research field described in this section is a cost–benefit analysis of various technical actions within an energy system, such as the installation of flexible loads, grid expansion actions or various additional storage capacity options, in terms of their grid and system supportability. In this analysis, the monetary costs of grid and system supportability will be calculated by comparing the improvement in the KPIs (GSI or SSI) with the total costs of the technical action. Building on this, concepts for state subsidization mechanisms could be developed, which consider the determined, real costs of grid or system supportability and thereby incentivizes corresponding projects.

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