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Quantifying the Operational Flexibility of Distributed Cross-Sectoral Energy Systems for the Integration of Volatile Renewable Electricity Generation

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Abstract: As a part of the transition in higher-level energy systems, distributed cross-sectoral energy systems (DCESs) play a crucial role in providing flexibility in covering residual load (RL). However, there is currently no method available to quantify the potential flexibility of DCESs in covering RL. This study aimed to address this gap by comparing the RL demand of a higher-level energy system with the electricity flow between a DCES and the electricity grid. This can allow for the quantification of the flexibility of DCES operation. Our approach was to categorize existing methods for flexibility quantification and then propose a new method to assess the flexibility of DCESs in covering RL. For this, we introduced a new quantification indicator called the *Flexibility Deployment Index* (FDI), which integrates two factors: the RL of the higher-level energy system and the electricity purchase and feed-in of a DCES. By normalizing both factors, we could compare the flexibility to cover RL with respect to different DCES concepts and scenarios. To validate the developed quantification method, we applied it to a case study of a hospital's DCES in Germany. Using an MILP optimization model, we analyzed the variation in FDI for different technology concepts and scenarios, including fixed electricity tariffs, dynamic electricity tariffs, and CO_2-emission-optimized operation. The results of our calculations and the application of the FDI indicate that high-capacity combined heat and power units combined with thermal storage units provide higher flexibility. Additionally, the results highlight higher flexibility provision during the winter period compared to the summer period. However, further application and research are needed to confirm the robustness and validity of the FDI assessment. Nonetheless, the case study demonstrates the potential of the new quantification method.

Keywords: distributed cross-sectoral energy system; flexibility; optimized operation; quantification indicator; residual load

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1. Introduction and Motivation

The aim of this work was to develop a method to quantify the flexibility provision of distributed cross-sectoral energy systems (DCESs).

According to [1], there are different types of flexibility demands in a higher-level energy system. In addition to frequency stabilization and congestion management, covering residual load (RL) is also considered a form of flexibility demand. In [2], the residual load P_{RL} in (1) results from the difference of electricity power consumption P_{el} and the renewable energy (RE) generation P_{RE}.

$$P_{RL} = P_{el,consumption} - P_{RE,generation} \quad (1)$$

Presently, in the higher-level energy system of Germany, the requirement for flexibility demand of RL is primarily fulfilled by conventional power plants, controllable RE, and storage power plants [3,4]. However, with the phasing out of coal and nuclear electricity generation in Germany [§ 4 art. 1 cl. 2 KVBG; § 7 art.1 AtG], significant flexibility capacities are going to vanish, leading to the emergence of a potential flexibility gap [5,6].

To address this challenge, one possible solution could be to explore the flexible operation of DCES. However, assessing the flexibility potential of a DCES is a non-trivial task due to the absence of a standardized method for evaluating DCES flexibility.

Pina et al. [7] defines energy systems as cross-sectoral when they include at least one polygeneration unit, such as a combined heat and power (CHP) unit, that can be supplemented by additional energy conversion units and storage. These systems are referred to as distributed energy systems when they serve as local energy systems. DCESs are primarily deployed in industrial, district, and building facilities with high energy demands, such as hospitals, swimming pools, universities, and shopping centers.

DCESs primarily serve the energy demand of their respective facilities. Any surplus capacity can be provided to the higher-level energy system and substitute flexible power plants as presented in [8]. However, since the availability of this capacity is time-dependent due to the volatile nature of facility demand, the flexibility potential of DCES cannot be accurately measured by their installed generation capacity alone.

To develop a suitable characteristic value, we firstly draft an understanding of flexibility in Section 1.1. Based on this, we define the flexibility of a DCES in Section 1.2. We provide a literature review, giving an overview of existing quantification methods in Section 1.3. We present various flexibility indicators and discuss whether they are sufficient for the targeted quantification. Subsequently, we define requirements for a new quantification indicator in Section 2.1 and deduce and introduce the Flexibility Deployment Index (FDI) in Section 2.2. In Section 2.3, we present a case study in which we perform a plausibility check of the quantification indicator, and in Section 3, we present the results of the case study. In Section 4, we conclude our results of the study.

1.1. Flexibility in the Energy System

In [9–12], flexibility is described as a balancing service for a higher-level energy system. The flexibility purpose is RE market integration and RE curtailment reduction by flexible electricity purchase and electricity feed-in by an energy system. Load-shifting is a technical implementation designed to offer this flexibility. Negative load-shifting is characterized by a reduction in electricity generation, an increase in load, and storage charging. Positive load-shifting is characterized by an increase in electricity generation, a reduction in load, and storage discharging. To gain flexibility by load-shifting, the requirements of the higher-level energy system need to be considered.

According to literature, flexibility provision can be divided into different characteristics ranging from capability services up to technical assertions:

1. *Flexibility options* are technologies and operating modes of different fields of function in the energy system that can provide flexibility [13–16]. Figure 1 shows an overarching definition of these technologies and operating modes and allocates them to the fields of flexible generators, flexible consumers (demand), flexible storage, and the expansion of the electricity grid. In this approach, the flexibility options cover RL.

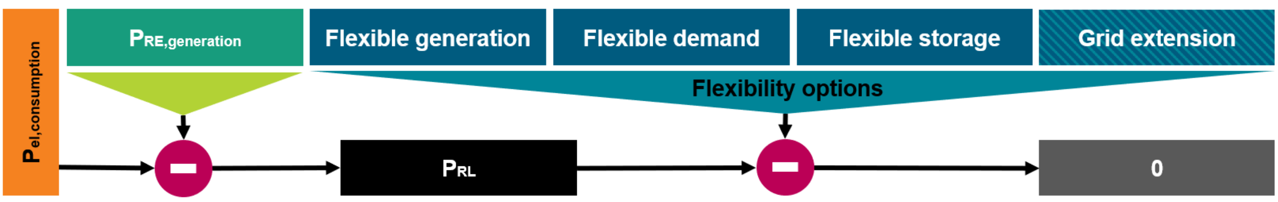

Figure 1. Fields of functions in an energy system with flexibility options covering RL. Figure in accordance with [17].

2. According to [18], three areas of *flexibility applications* exist. They describe the point of view of a flexibility option:
    - *Market -serving flexibility* does not depend on any physical necessity. It is exercised solely by preferences on the demand side. It comprises the operation of individual market players, who optimize their operation following an objective function regarding external signals (e.g., electricity price and CO_2 emissions).
    - *System-serving flexibility* is intended to ensure the quality of supply in the electricity grid and thus the security of supply. The main objective is to maintain the frequency by using balancing power for the stability of the system balance of generation and demand. One instrument for providing system-serving flexibility are operating reserves.
    - *Grid-serving flexibility* is provided by the transmission system operators for energy system stability. The focus is on grid congestion management for the interconnected systems and the prevention of bottlenecks. For example, in Germany, one instrument for providing grid-serving flexibility is 'Redispatch'.
3. According to [12,19], flexible operation can be provided on different *flexibility levels* in the energy system - the consumer, producer, and storage level.
    - The *consumer level* includes mainly energy demands. Consumer level flexibility can be divided into consumption-side flexibility and load management. These are differentiated by their influence on the energy consumer. The consumption-side flexibility has no influence on the consumer's behavior, as it results from flexibility of the energy supply units on the demand side. In contrast, load management, also called demand-side management (DSM), has an impact on the demand time series and thus has an impact for the consumer and the consumer's behavior. The consumer level can also be named the *prosumer level* , if the consumer is also able to provide electricity to the grid.
    - The *producer level* includes controllable power plants that can be operated flexibly without external constraints.
    - The *storage level* includes large-scale storage facilities that can store electrical energy directly or indirectly and thus provide storage flexibility.
4. In [20–22], the term *flexibility potential* is defined as the flexibility that a flexibility option can theoretically provide. The authors of [21] defined flexibility potential in terms of technical potential, technically usable potential, socio-technical potential, economic potential, and regulatory potential. The authors of [20] related these to each other as shown in Figure 2. In this sense, the differentiation of technical potential from theoretical potential is in accordance with the technical restrictions of the flexibility option. The technical potential is further constrained by the frequency of its flexibility call-ups, defined as the technical usable potential. The technically usable potential is finally reduced to the usable potential by the economic, socio-technical, and regulatory potential. The economic restrictions of the technical usable potential are affected by the economic viability of a callable flexibility option, which is mainly characterized by the revenue of flexibility provision. The socio-technical potential is the willingness of adjusting operation and services for providing flexibility and depend on the extent to which the provision of flexibility leads to restrictions in normal operation or the original intended use of the flexibility option. The regulatory restrictions are defined by legislations of authorities and regulations of market access.

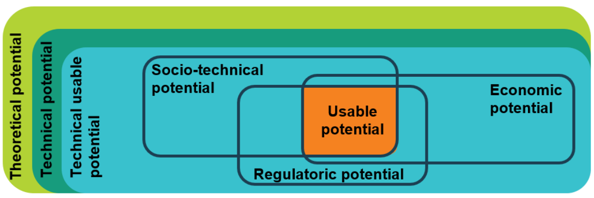

Figure 2. Classification of different flexibility potentials, in accordance with [20].

1.2. Flexibility of a DCES

In this section, we classify the flexibility offered by a DCES considering the supply of electricity, heating, and cooling for a facility, and we formulate an understanding of why and how a DCES flexibility covers RL.

In this study, the DCES is containing energy conversion and storage technologies in the form of a CHP, a gas boiler, a compression chiller (CC), and thermal energy storage units (TESs). Every unit represents a flexibility option: The CHP unit, the gas boiler, and the CC are flexible generators. The TESs are flexible storage units. In the following, we consider the entire DCES as one flexibility option. The DCES can thereby provide flexibility to the higher-level energy system by the electricity flows through the public grid connection.

As the focus in this study is on the cost-minimal operation, the flexibility application of the DCES operation can be understood as market-serving flexibility. Though it should be noted that market-serving flexibility can also be interpreted as system-serving flexibility, as markets for balancing energy exist. According to [23], a DCES can also run in a grid-serving manner by considering grid bottlenecks. In this case, they might be installed close to consumers.

The flexibility level of the DCES is the consumer level providing consumption-side flexibility. The DCES offers load-shifting by sector coupling with the CHP and time flexibility with the TES. As no active adjustment of the demand time series exists, DSM is not possible.

In this study, we focus on the usable flexibility potential of the DCES. The economic and regulatory framework conditions are mainly determined by the electricity markets. The socio-technical restrictions are set by the premise that the facility's demand needs to be fulfilled at any time.

Based on this classification, we formulate an understanding of the flexibility of a DCES in this study in an application context: *Constrained by the socio-technical, regulatory, and economic restrictions, the DCES contains a usable flexibility potential of market-serving consumption-side flexibility. The flexibility provision does not primarily follow a physical necessity. It follows the optimal operation of the DCES. The optimized operation is controlled by an external signal under the premise that all DCESs' facility energy demands are covered at any time. Dependent on the DCESs' energy conversion technologies and storage units, the DCES operation covers RL in the higher-level energy system and thus becomes a flexibility option.*

1.3. Review of Flexibility Indicators

There are several approaches in the literature to quantify the flexibility of distributed cross-sectoral energy systems (DCESs). These approaches have different interpretations of flexibility and pursue different flexibility objectives, resulting in a variety of indicators.

Some indicators have a more generic focus. In the study of Schlachtenberg et al. (2016) [24], the indicator used focuses on the timescale to cover RL. While in Zöphel et al. (2018) [25], the quantification is more focused on the framework condition of the considered higher-level energy system. Another top-down quantification approach is used in Boblenz et al. (2019) [26] where only the flexibility demand of the higher-level energy system is quantified. Additionally, studies by Perera et al. (2019) and Yang et al. (2023) [27,28] use different flexibility indicators to evaluate the design decisions of DCESs.

Other studies use different indicators to quantify the operational flexibility of a DCES, but with a different understanding of flexibility from what is presented in Section 1.2. In Tables A1 and A2, we list these indicators and their characteristics. We have adjusted the nomenclature to improve comparability.

The existing indicators to quantify the operation of a DCES are valid for different time periods. We begin with the quantification of points in time in [29–34], the period of the flexibility provision in [35,36], and the quantification of a freely selectable period in [31,32,35,37–40]. The indicators also differ in the use of a reference operation or no reference operation in [29–33,35,39,40]. Based on the different approaches, the number and type of used parameter also vary. In [29,35,36], only the time t of a flexibility provision is considered, and in [29–33,35], the power generation P is also taken into account. In [31,32,35,37,38], the parameters of time and power are combined in order to quantify flexibility using the parameter of energy E. In [31,34,37–40], external parameters of mostly cost signals and electricity prices are also used. A distinction can also be made between relative result values in [29–31,38–40] and absolute result values in [31–37] with parameters of the units time, power, energy, or costs.

The indicators from the literature can be categorized into indicators for time flexibility in [29,35,36], power flexibility in [29–33,35,41], energy flexibility in [31,32,35,37,38], energy efficiency in [31,32,34], and the quantification of flexibility through external variables or signals in [31,37–40]. The indicators for time flexibility, power flexibility, energy flexibility, and energy efficiency focus on flexibility definitions concerning only single energy units or separate energy systems. Only the quantification indicators of flexibility through external variables or signals consider a higher-level energy system. However, RL is not considered in any of these indicators.

None of the studies conducted thus far have presented indicators that enable the quantification of the flexibility of a DCES in covering RL.

In this study, our objective was to develop a bottom-up quantification approach specifically for DCESs. We aimed to quantify the operation of the DCES and determine whether it successfully reduces RL in a higher-level energy system or increases the demand for RL. Our focus is solely on quantifying the operation of the DCES, which will enable us to compare different operation modes of various types of DCESs.

2. Method

As no adequate flexibility indicator exists in the literature to quantify the above defined flexibility, we determined a new indicator.

2.1. Requirements for a New Quantification Indicator

The new indicator is intended to quantify the extent to which the market-serving flexibility of a DCES covers the RL of a higher-level energy system. The indicator should enable the quantification of the usable flexibility potential. The focus is on quantifying the concurrence of the DCES operation with a higher-level energy system. The indicator should be able to distinguish between positive and negative load-shifting at times with high or low RL. Due to the wide range of other possible DCES configurations, it is important that the quantification takes place on the basis of parameters that are applicable for a wide variety of DCES concepts. As the flexibility understanding focuses on the electricity sector, the used parameters should also be electrical values. The indicator should provide comparability of different DCESs in different facilities and in different operation modes. Therefore, it is advisable to use normalized values. Usually, this leads to an appropriate outcome between zero and one, which presents the results in a clear and meaningful way. Further, the indicator should work for different quantification periods (QPs).

2.2. The Flexibility Deployment Index

We developed a new quantification indicator: the *Flexibility Deployment Index* (FDI). It consists of different electrical parameters. We considered the electrical load-shifting through the grid connection of the DCES to and from a higher-level energy system, and we also considered the system's RL. Therefore, we set the system boundary around all DCES units and considered the DCES as a black box.

We represent the flexibility offer with the load-shifting of the DCES by the *Flexibility Potential Factor* ($F_{DCES,t}$). As can be seen in (2), the $F_{DCES,t}$ includes the electricity purchase P_{pur} and the electricity feed-in P_{in} of the DCES at a time step t within a QP as the set of all time steps. To align the power with the capacity of the DCES and its facility's demand, we normalize the power with the maximum electricity flow $P_{DCES,max}$ into and out of the DCES within the QP. We define $P_{DCES,max}$ in (3). The denominator is determined by a case distinction, depending on whether power is purchased or fed in. If power is fed in (positive numerator), the maximum power feed-in during the QP is used as the denominator. If power is purchased (negative numerator), the maximum purchased power in the QP is used as the denominator. The $F_{DCES,t}$ has a possible range from -1 to +1, where -1 represents the maximum possible flexibility potential from negative load-shifting, and +1 represents the maximum possible flexibility potential from positive load-shifting.

$$F_{DCES,t} = \begin{cases} \dfrac{P_{in,t} - P_{pur,t}}{|P_{DCES,max}|} & \text{if } P_{DCES,max} \neq 0 \\ 0 & \text{if } P_{DCES,max} = 0 \end{cases} \tag{2}$$

with $P_{DCES,max}$ as follows:

$$P_{DCES,max} = \begin{cases} \max\limits_{t \in QP}(P_{in,t}) & \text{if } P_{in,t} - P_{pur,t} > 0 \\ \max\limits_{t \in QP}(P_{pur,t}) & \text{if } P_{in,t} - P_{pur,t} < 0 \end{cases} \tag{3}$$

We represent the flexibility demand for covering RL in the higher-level energy system by the *Residual Load Factor* ($F_{RL,t}$). As can be seen in (4), the $F_{RL,t}$ includes the ratio of the RL $P_{RL,t}$ at a time step t to the absolute value of the maximum positive or negative RL $P_{RL,max}$ within a QP. We define $P_{RL,max}$ in (5) and apply a case distinction. If the RL is positive at a time step t, the maximum RL of the QP is used for $P_{RL,max}$. If the RL is negative, the minimum RL of the QP is used for $P_{RL,max}$. Accordingly, the $F_{RL,t}$ differentiates between positive and negative RL. It has a possible range of values from -1 to +1, where -1 corresponds to the maximum need for negative load-shifting, and +1 corresponds to the maximum need for positive load-shifting.

$$F_{RL,t} = \begin{cases} \dfrac{P_{RL,t}}{|P_{RL,max}|} & \text{if } P_{RL,max} \neq 0 \\ 0 & \text{if } P_{RL,max} = 0 \end{cases} \tag{4}$$

with $P_{RL,max}$ as follows:

$$P_{RL,max} = \begin{cases} \max\limits_{t \in QP}(P_{RL,t}) & \text{if } P_{RL,t} > 0 \\ \min\limits_{t \in QP}(P_{RL,t}) & \text{if } P_{RL,t} < 0 \end{cases} \tag{5}$$

As a typical DCES provides electricity predominantly in a kW or low MW range and the RL is to be classified in a high MW or GW range, normalizing the values of the load-shifting of the DCES and of the RL of the higher-level energy system by F_{DCES} and F_{RL} allows for an appropriate comparison of the DCES' flexibility offer and the flexibility demand of the higher-level energy system. Dividing the flexibility demand F_{RL} with the flexibility offer F_{DCES} results in a value that describes the correlation of flexibility demand and flexibility offer. For this value, we use the term *Flexibility Deployment Index* (*FDI*). Directly comparing the absolute values would result in very small values, which would impede the comparability. Thereupon, the FDI_t in (6) puts the technical flexibility offer of a DCES and the flexibility demand of the higher-level energy system's RL in relation to each other.

$$FDI_t = \begin{cases} 1 & \text{if } FDI_{k,t} > 1 \\ FDI_{k,t} & \text{if } 1 \leq FDI_{k,t} \leq -1 \\ -1 & \text{if } FDI_{k,t} < -1 \end{cases} \text{ with } FDI_{k,t} = \begin{cases} \dfrac{F_{DCES,t}}{F_{RL,t}} & \text{if } F_{RL,t} \neq 0 \\ 0 & \text{if } F_{RL,t} = 0 \end{cases} \tag{6}$$

A positive value indicates that the DCES load-shifting does cover the RL of the higher-level energy system, and a value of +1 corresponds to a maximum possible RL coverage by the DCES. A negative value indicates that the DCES load-shifting does not cover the RL of the higher-level energy system, and a value of −1 corresponds to a maximum addition of RL by the DCES. Due to the division of the two factors, an FDI_t greater than 1 would occur in the case that $F_{RL,t}$ is smaller than $F_{DCES,t}$. In this case, the assumption is made that even with a small $F_{RL,t}$, the absolute RL exceeds the absolute power flow of the DCES. Accordingly, in cases where $F_{DCES,t}$ and $F_{RL,t}$ both have a positive or a negative algebraic sign, it results in a positive effect for the higher-level energy system. If the factors have different algebraic signs, the FDI_t is negative.

Averaging the values of FDI_t over the number of all time steps n_{QP} in (7) results in the *average Flexibility Deployment Index* $\overline{FDI}$. It shows the mean FDI over the QP and results in a value between −1 and +1.

$$\overline{FDI} = \frac{\sum_{t \in QP} FDI_t}{n_{QP}} \tag{7}$$

2.3. Case Study

To apply the defined flexibility indicator, we carried out a case study for the DCES of a hospital in Hattingen, Germany. The hospital includes around 270 beds. The demand data were obtained from measurements of the hospital. Its heat consumption was 4239 MWh, and its electricity consumption was 2457 MWh per year. We examined two different energy system concepts of the DCES in three tariff scenarios and performed the calculation for one year at a resolution of 15 min.

To determine the operation of the DCES, we use a mixed integer linear programming (MILP) optimization model. We created the DCES models with our self-developed optimization tool ESyOpT, which is based on the Python optimization-modelling library Pyomo [42] and the open energy modelling framework oemof [43]. With the mathematical solver Gurobi [44], we calculated the optimized operation for the minimum operating costs and for the minimum CO_2 emissions of the optimized electricity and natural gas purchase and feed-in. In order to minimize CPU time, we implemented rolling horizons with a duration of three days and 182 time periods for a year. The computations were completed in just 15 min on an i5-8350U CPU running at 1.70 GHz.

2.3.1. Demand Time Series

For the input demand time series, we used the electricity, heating, and cooling demands of the hospital measured in [45]. The input demand data for one exemplary year had an electricity base load of about 250 kW and an electricity peak load of about 400 kW. The heating base load was about 350 kW in the summer and about 650 kW in the winter. Cooling was predominantly needed in the summer. The cooling base load was around 35 kW at night. During the day, the demand would rise to a peak of about 75 kW.

2.3.2. Energy System Concepts

In the case study, we considered two DCES concepts that each included a CHP, a gas boiler, an emergency cooler, a CC, a TES for heating, and a TES for cooling. The unit interdependencies were analyzed in [45]. As depicted in Table 1, we conceptualized one reference concept (*ref*) and one optimized concept (*opt*), which enables a flexible operation. The *ref* concept included a CHP with an electrical nominal load of the electrical base load of the hospital. The *opt* concept included a CHP with an electrical nominal load of the electrical peak load of the hospital.

Table 1. Units and parameters of the concepts in the DCES model.

Concepts	$CHP_{Nominal\ Load}$		$CHP_{Part\ Load}$	Gas Boiler	Heating TES	Emergency Cooler	CC	Cooling TES
	kW_{el}	kW_{th}	%	kW_{th}	kWh_{th}	-	kW_{th}	kWh_{th}
ref	250	348	n.a.	1500	n.a.	yes	600	n.a.
opt	400	557	50–100	1500	519	n.a.	600	95

2.3.3. Scenario Time Series

We carried out the optimization for different tariffs. As depicted in Table 2, we used two electricity price tariffs and one tariff, which implies the CO_2 emission factor (EF). Furthermore, for the quantification with the FDI, we used an appropriate RL time series.

Optimization Tariff Scenarios

We optimized the DCES operation according to the minimal costs and the minimal CO_2 emissions. To simulate the actual tariff structures, we used a fixed price tariff (*fix*), including a fixed price for electricity and natural gas. To simulate the optimized market-led operation of the DCES, we used a dynamic electricity tariff (*dynamic*) and an *EF* time series of the higher-level energy system.

The *fix* tariff included a fixed electricity price of 17.9 ct/kWh for electricity purchase and a revenue of 15.5 ct/kWh for electricity feed-in of the DCES. We adjusted the prices to the mean prices of the *dynamic* tariff to keep the same price level. The purchase and feed-in prices varied according to taxes and levies.

The *dynamic* tariff included the German intraday auction market price of 2021 (see Figure 3a). The mean purchase price was 17.9 ct/kWh, and the mean feed-in revenue was 15.5 ct/kWh. The volatility was 1.42 ct/kWh determined by the hourly standard deviation. The purchase and feed-in prices varied according to taxes and levies.

The *EF* tariff included the specific CO_2 emissions of the marginal power plant in the merit order in every time step, by the approach of [46] (see Figure 3a). We used data of [47–49] for the German electricity mix in 2021. Therefore, we used an average marginal EF of 589.1 g_{CO_2}/kWh, which ranks between the EF of conventional gas turbines (EF = 619 g_{CO_2}/kWh) and combined cycle gas turbines (EF = 411 g_{CO_2}/kWh). The maximum EF was 1093 g_{CO_2}/kWh for lignite-fired power plants, and the lowest EF was 0 g_{CO_2}/kWh for RE power plants. No EF for the electricity feed-in of the DCES was needed to calculate the optimized operation.

In all tariffs, we used a fixed natural gas price of 3.77 ct/kWh with an EF of 201 g_{CO_2}/kWh [47].

Table 2. The *fix, dynamic*, and *EF* tariffs are the external signals for the optimization model.

Tariff	el. Purchase	el. Feed-In	Volatility [a]	Natural Gas
fix	17.9 ct/kWh	15.5 ct/kWh	-	3.77 ct/kWh
dynamic	ϕ 17.9 ct/kWh	ϕ 15.5 ct/kWh	1.42 ct/kWh	3.77 ct/kWh
EF	ϕ 589.1 g_{CO_2}/kWh	-	90.06 g_{CO_2}/kWh	201 g_{CO_2}/kWh

[a] hourly standard deviation.

Residual Load Time Series

For calculating the FDI in every timestep, we required the time-specific RL (P_{RL}). As the RL depends on the net electricity consumption ($P_{el,consumption}$) and the RE electricity generation ($P_{RE,generation}$), we used consumption and generation data from [50] for 2021. Figure 3b shows the composition of the average RL for the winter time, the summer time, and for one year.

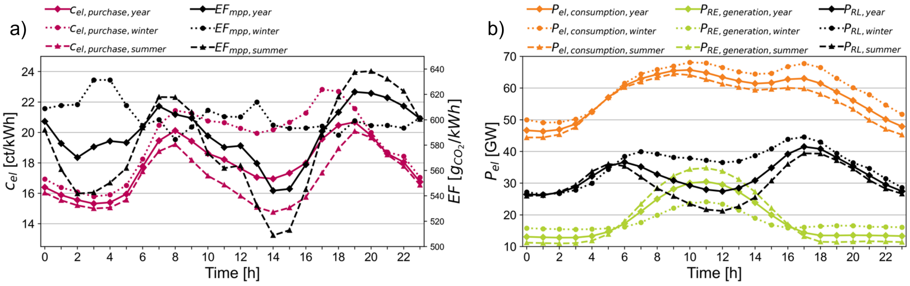

Figure 3. (**a**) Hourly average electricity costs and hourly average EF. (**b**) Composition of the hourly average RL.

3. Results

We calculated the DCES' operation modes of the different concepts and scenarios and determined the FDI for each operation.

3.1. FDI Dependency on Unit Operation and RL Demand

We analyzed the changes of the FDI_t in accordance with the DCES operation and the RL of the higher-level energy system. Figure 4a shows the DCES electrical key figures in quarter-hourly resolution of the *opt* concept in the *EF* tariff and the absolute RL for an exemplary day in winter. Figure 4b shows the corresponding $F_{DCES,t}$ and $F_{RL,t}$ for every time step resulting in the FDI_t.

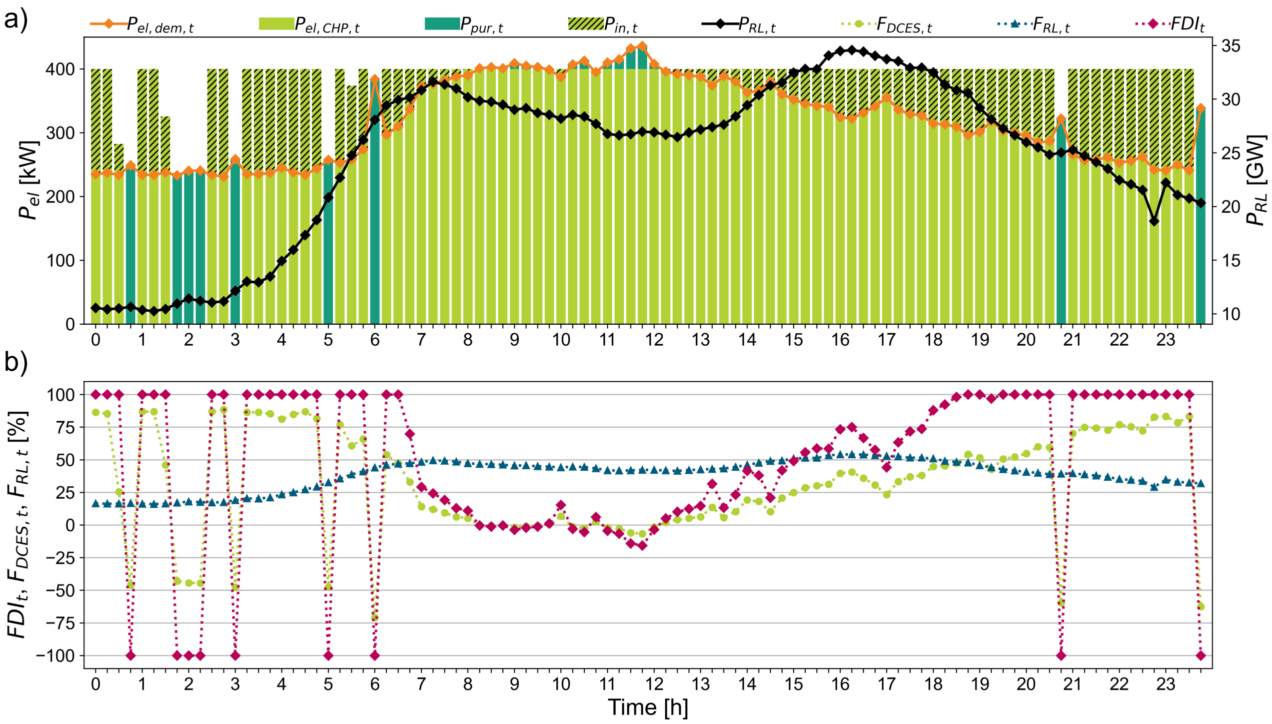

Figure 4. (**a**) The DCES electrical key figures in quarter-hourly resolution of the *opt* concept in the *EF* tariff and the absolute RL for an exemplary day in winter. (**b**) The corresponding $F_{DCES,t}$ and $F_{RL,t}$ for every time step result in the FDI_t.

Due to the high heat demand in winter, the CHP unit operates almost continuously at nominal load. However, in some time steps, the CHP operation becomes restricted by the *EF* tariff optimization. This CHP restrictions result in an additional electricity purchase. A detailed analysis of the DCES unit operation modes can be found in [45].

Table 3 shows the resulting values of the FDI_t for selected time steps. Among others, in the time steps at 04:00 a.m. and 06:45 a.m., a positive $F_{DCES,t}$ is present resulting from the electricity generation and surplus feed-in. In the cases of no electricity generation at 00:45 a.m. or additional electricity purchase at 11:30 a.m., the $F_{DCES,t}$ becomes negative. Since the RL is positive for the whole day, the $F_{RL,t}$ is also positive in every time step.

Table 3. FDI_t calculation for single time steps of Figure 4.

Time Step, t	$F_{DCES,t}$, %	$F_{RL,t}$, %	FDI_t, %
00:45 a.m.	−45.9	16.7	−100
04:00 a.m.	81.2	23.4	100
06:45 a.m.	33.0	47.3	69.8
11:30 a.m.	−5.9	41.9	−14.1

At 06:45 a.m., the DCES feeds electricity into the public grid, and a positive RL exists in the higher-level energy system. This coherency supports RL coverage. Therefore, the FDI_t results in a positive value of 69.8%. At 04:00 a.m., the DCES operation covers the RL even more as now the $F_{DCES,t}$ is greater than the $F_{RL,t}$. The FDI_t is at 100%.

A positive $F_{RL,t}$ and a negative $F_{DCES,t}$ result in a negative FDI_t. At 11:30 a.m., the RL is similar as at 06:45 a.m., but now the DCES purchases additional electricity from the grid resulting in more RL for the higher-level energy system. Therefore, the FDI_t results in a negative value of −14.1%. At 00:45 a.m., the absolute value of $F_{RL,t}$ is smaller than the absolute value of $F_{DCES,t}$ but with different signs. The FDI_t is at −100%.

3.2. Flexibility Assessment over the Quantification Period

As shown in Figure 5, we calculated the $\overline{FDI}_{QP}$ of the case study for the winter time, the summer time, and one year.

As the *ref* concept contains a CHP with low nominal load and no TES, almost no load-shifting is possible. Therefore, the operation mode in every tariff optimization is the same, and the $\overline{FDI}_{QP}$ of the *ref* concept is also the same in all operation modes.

Accordingly, in the *ref* concept, electricity feed-in occurs only in a few time steps when the electricity demand is as low as the nominal load of the CHP. In most other cases, electricity is purchased, as the demand is mostly as high as the generation. Thus, no differences in operation modes are possible, and the FDI is mainly dependent on the facility's demand and the RL. This results in a FDI of −15.4% for one year for the *ref* concept. This result shows that the DCES operation is increasing the RL instead of reducing it.

The *opt* concept is useful for covering RL in the QP of one year in all tariffs, as the $\overline{FDI}_{year}$ results in positive values. The highest value for $\overline{FDI}_{year}$ is achieved for the operation mode in the *dynamic* tariff, followed by the *EF* and the *fix* tariffs.

The seasonal differences result primarily from the different heating demands of the facility. In the *opt* concept, the CHP generates more electricity in the winter time, as it has lower restrictions in terms of its heat excess. In the summer time, the heat demand of the facility is lower, so the generated electricity by the CHP is lower. This reduces the number of time steps with a positive FDI_t.

In the *opt* concept, only slight differences exist between all tariffs. Although the operation mode regarding the *fix* tariff achieves the lowest $\overline{FDI}_{year}$, the $\overline{FDI}_{winter}$ is higher than in the other tariffs. As Pagnier and Jacquod [51] have proven a correlation between the RL and the electricity stock-market price in an energy-only-market, we expected the highest $\overline{FDI}$ in the optimized operation modes regarding the *dynamic* tariff in every QP. We also expected the $\overline{FDI}$ in the *EF* tariff to be higher than in the *fix* tariff in every QP, as the *EF* might be connected with the RL. However, the $\overline{FDI}_{winter}$ is highest in the *fix* tariff. This indicates that, although the DCES operations have been optimized according to an external signal that supposedly correlates with the RL, the operations still do not result in an optimized operation mode regarding the RL. Because of the volatility in the *flex* and *EF* tariffs, the data show an arbitrage trading in the optimized operation modes using the TES. This arbitrage trading is at the expense of RL coverage resulting in a lower $\overline{FDI}_{winter}$ compared to the $\overline{FDI}_{winter}$ in the *fix* tariff.

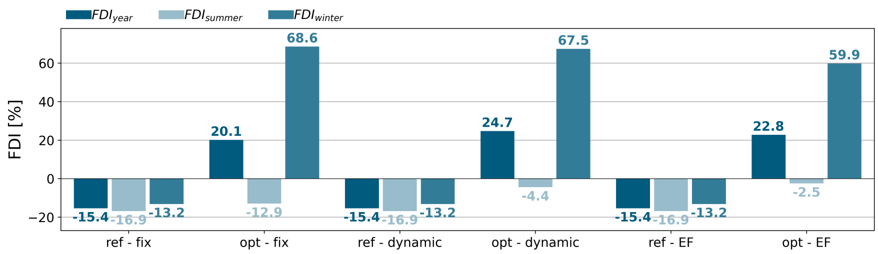

Figure 5. The FDI of relevant QPs for two concepts in three tariff scenarios. The $\overline{FDI}$ is presented for the QP of one year, the summer time. and the winter time.

4. Conclusions and Discussion

With the FDI, we provide a new method to quantify the flexibility of DCES operation in covering the RL of the higher-level energy system. As one element of power system transitions, optimized DCES operation regarding the best possible FDI might thus cover RL and potentially substitute flexible fossil-powered energy plants. To deduce the FDI, we formulated different understandings of flexibility and presented a definition of flexibility considering the characteristics of a DCES. In this definition, we have taken into account the usable flexibility potential of a DCES and its flexibility level as a consumer, possibly a prosumer. We have considered the flexibility of the DCES' operation modes and its connection with the higher-level energy system. We have noted that a DCES can be a flexibility option for covering RL in the higher-level energy system with a flexibility potential.

Based on the literature review conducted for this study, it can be concluded that there are currently no quantification methods available to assess the flexibility of DCES operations to cover the RL of the higher-level energy system. This knowledge gap emphasizes the necessity for a new metric that can measure the flexibility of a DCES in terms of its ability to cover RL. Unlike other flexibility indicators, the FDI allows for a quantification without a reference concept. Due to the use of normalized factors, it might be valid to compare the FDI of a DCES with other DCESs of different facilities that include different units (e.g., a heat pump, an absorption chiller, etc.) and variations in capacity within the same higher-level energy system's RL scenario.

In response to this gap, this paper introduces the FDI as a new metric to quantify the flexibility of a DCES in covering RL. The FDI takes into account the factors of electricity load-shifting of the DCES and the RL of the higher-level energy system. By normalizing the factor, it becomes possible to compare these. Initial case studies demonstrate the potential of the FDI in assessing the flexibility of DCES operations. The results of the case study show that a higher electricity generation capacity and a larger storage unit capacity in a DCES lead to a higher FDI. However, further application is required to confirm the robustness and usefulness of the FDI across different contexts. As, in this study, the FDI was only applied for two DCES concepts of the same facility.

To apply the FDI calculation in practice, it is only possible post-priori when both the DCES operation and the time series of RL are known. Therefore, to calculate the FDI for future operation, a forecast must be used. It is important to note that the DCES operation optimization in this study is not for live operation, but rather for the purpose of demonstrating the potential of the FDI.

In order to obtain the best possible FDI result by optimizing the DCES operation. It might be necessary to define an objective function that displays the relationship between load-shifting and RL. Dynamic tariffs provide a practical approach in this regard, as they can incentivize load-shifting behaviours. The consideration of CO_2 emissions of the marginal power plant also contributes to the FDI calculation. As Pagnier and Jacquod [51] have proven a correlation between the RL and the electricity stock-market price in an energy-only-market, it was to be expected that an optimized operation regarding a dynamic tariff might also lead to a higher FDI. However, the effect was low compared to changing the DCES electricity generation and storage units. Only minor differences between a fix and a dynamic tariff could be noted. Furthermore, the optimization regarding CO_2 emissions of the marginal power plant led only to little changes in the FDI. An optimization regarding the average CO_2 emissions of the electricity mix might lead to a higher FDI, but has to be investigated further. Furthermore, the RL of the higher-level energy system has an influence on the FDI, as it varies regarding the RL curve of the considered QP. It might be helpful to define an appropriate reference QP when using the FDI to compare different DCES operations. However, to achieve the best possible results, an even closer objective function is necessary, which takes into account additional factors and their impact on the FDI.

The FDI provides a stepping stone towards an improved integration of DCES that supports renewable energy growth. By quantifying the flexibility of DCES operations, the FDI can aid in optimizing the operation of DCES systems and potentially substitute the need for flexible fossil-powered energy plants. It allows for a standardized measure of flexibility, enabling comparisons between different DCES concepts and facilities. However, it is important to note that the FDI needs to be validated and refined in different scenarios and market designs to ensure its reliability and applicability.

In summary, with the FDI, we have developed an indicator to quantify the flexibility of covering RL regarding the higher-level energy system. While the FDI shows promise in evaluating the flexibility of DCES operations, further research is needed to validate its effectiveness and explore its potential in different energy applications and market designs. The FDI has the potential to contribute to the optimization of DCES operation and facilitate the transition towards renewable energy sources.

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Nomenclature & Abbreviations

The following abbreviations are used in this manuscript:

CC	compression chiller
CHP	combined heat and power unit
DCES	decentral cross-sectoral energy system
dem	electricity demand
DSM	demand-side management
dynamic	dynamic electricity price tariff
E	Energy
el	electricity
EF	emission factor
F_{DCES}	flexibility potential factor
F_{RL}	residual load factor
FDI	flexibility deployment index
$\overline{FDI}$	average flexibility deployment index
fix	fixed electricity price tariff
in	electricity feed-in
k	cases
P	power
max	maximum
MILP	mixed integer linear programming
mpp	marginal power plant
n	number of time steps
opt	optimized concept
pur	electricity purchase
QP	quantification period
RE	renewable energy
ref	reference concept
RL	residual load

t	time step
th	thermal
TES	thermal energy storage

Appendix A. Review Tables

Table A1. Review of the quantification indicators of time, power, and energy.

Source	Formula	Unit	Characteristics
[29,35,36]	$\Delta t_+ / \Delta t_-$	[h]	• Forced operational flexibility Δt_+ describes the time a generation unit can operate at maximum power until a storage unit is completely charged. Delayed operational flexibility Δt_- describes the time a generation unit can stay switched off until a storage unit is completely discharged. • Exclusive quantification of a storage unit. • Data of several technologies within the energy system are necessary.
[31–33,35]	$\Delta P_t = P_{flex,t} - P_{ref,t}$ $\Delta P_{+,t} = P_{flex,t} - P_{ref,t}$ $\Delta P_{-,t} = P_{ref,t} - P_{flex,t}$	[kW]	• Power shifting (ΔP_t) of an energy system in flexible operation ($P_{flex,t}$) compared to an energy system in a refernce operation ($P_{ref,t}$) • Load shifting is a measure for the instantaneous energy flexibility. Quantification of single events. • $\Delta P_{+,t}$ is the positive load shift and $\Delta P_{-,t}$ the negative load shift.
[29,30]	$PSP = \frac{P_{flex,t} - P_{ref,t}}{P_{ref,t}}$	[-]	• Power Shifting Potential (PSP) indicates the relative load shifting capability. • PSP < 0: negative PSP • PSP > 0: positive PSP
[36,41]	$\Delta P_t = P_{max,t} - P_{min,t}$	[kW]	• ΔP_t determines the difference between a maximum ($P_{max,t}$) and minimum power curve ($P_{min,t}$). • Requires max. and min. reference power curves.
[31,32,35,37]	$\Delta E = \int_{t_0}^{t_{flex}} P_{flex}(t) - P_{ref}(t)\mathrm{d}t$	[kWh]	• ΔE states the power-shifting over a certain period. • The meaning depends on the selection of the period. • Depending on the period selection, positive and negative flexibilities can disperse each other.
[38]	$ESP = \frac{\sum_{t=1}^{n} \max(P_{ref,t} - P_{flex,t}, 0)}{\int_{t=1}^{n} P_{ref,t}\mathrm{d}t}$ $E_{flex} = \frac{\sum_{t=1}^{n} s_t \cdot (P_{ref,t} - P_{flex,t})}{\sum_{t=1}^{n} s_t \cdot P_{ref,t}}$	[%]	• Energy Shifting Potential (ESP) indicates the relative energy shifting capability. • E_{flex} multiplies the difference between the flexible power and the reference power with an external signal (s_t) and sets this in relation to the reference power multiplied by s_t. • Thus, the E_{flex} can indicate cost savings or additional costs over a freely definable period by using a cost function.
[34]	$PSE = \frac{P_{flex(s_t)} - P_{ref}}{E_{flex(s_t)} - E_{ref}}$	[1/h]	• The PSE indicates a power gradient and describes the ability of a power system to adapt to an external signal (s_t) at a given point in time.

Table A2. Review of the quantification indicators of costs and efficiency.

Source	Formula	Unit	Characteristics
[31]	$\eta_{storage} = \frac{\sum \int_{t_0}^{t_{discharge}} P_{flex}(t) - P_{ref}(t)\mathrm{d}t}{\sum \int_{t_0}^{t_{charge}} P_{flex}(t) - P_{ref}(t)\mathrm{d}t}$	[%]	• The storage efficiency is an indicator of the flexible use of the stored energy that compensates other energy generation units. • The difference between the stored energy in flexible and reference operation over the period of storage discharge is set in relation to the difference between the stored energy in flexible and reference operation over the period of storage charging. • The storage efficiency indicates the efficient use of storage heat. The ratio between discharging and charging events over the control horizon is defined as storage efficiency or shifting efficiency.
[32]	$\eta_{signal} = 1 - \frac{\int_{t_0}^{t_{flex}} P_{flex}(t) - P_{ref}(t)\mathrm{d}t}{\int_{t_0}^{t_s} P_{flex}(t) - P_{ref}(t)\mathrm{d}t}$	[%]	• Sets energy use over the entire period in relation to the use up to the external signal. • Exclusive quantification via flexibility option storage. • Definess the fraction of the heat that is stored during the flexibility event that can be used subsequently to reduce the heating power needed to maintain thermal comfort.
[37]	$K = \int_{t_0}^{t_{flex}} (k_{el} \cdot P_{el} + k_j \cdot P_j)\mathrm{d}t$ $\Delta K = K_{flex} - K_{ref} \leq 0$	[€]	• Deviations from the optimized reference operation are leading to additional costs. Following the reference operation representing the minimum costs. • The underlying cost function (k_j) contains the costs for required electricity and energy carriers.

Table A2. *Cont.*

Source	Formula	Unit	Characteristics
[31,39]	$FF = \frac{\int_{t_0}^{t_{lowprice}} P(t)\mathrm{d}t - \int_{t_0}^{t_{highprice}} P(t)\mathrm{d}t}{\int_{t_0}^{t_{lowprice}} P(t)\mathrm{d}t + \int_{t_0}^{t_{highprice}} P(t)\mathrm{d}t}$	[%]	• The flexibility factor FF assesses the operation of different energy systems in terms of their cost efficiency by showing how energy consumption can be shifted from high price periods to low price periods. • The FF varies between −1 and 1 whereas −1 correlates to a highly inflexible controlled system and 1 indicates highest desired flexibility.
[40]	$FI = 1 - \frac{K_{flex}}{K_{ref}} = 1 - \frac{\int_{t_0}^{t_{flex}} s_t \cdot c_{flex}(t)\mathrm{d}t}{\int_{t_0}^{t_{flex}} s_t \cdot c_{ref}(t)\mathrm{d}t}$	[%]	• FI gives a relative comparison of the costs of a flexible operation and of a reference operation. • s_t is the binary variable of the external signal.

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