PROCEEDINGS OF ECOS 2023 - THE 36TH INTERNATIONAL CONFERENCE ON
EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS
25-30 JUNE 2023, LAS PALMAS DE GRAN CANARIA, SPAIN

Quantifying operational flexibility of distributed cross-sectoral energy systems for the integration of volatile renewable electricity generation

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Abstract:

As one element of power system transition, distributed cross-sectoral energy systems (DCES) can provide flexibility for the electricity market. So far, no applicable method for quantifying the flexibility potential of DCES operation exists. Nonetheless, by comparing the flexibility demand of the electricity market and the electricity flow between a DCES and the electricity grid it becomes possible to quantify market-serving flexibility of DCES operation. In this work, we categorize aim and scope of already known flexibility quantification methods and develop a new method to assess DCES market-serving flexibility covering residual load (RL). Part of this method is the new developed quantification indicator *Flexibility Deployment Index* (FDI), integrating two factors: The RL of the electricity market and the electricity purchase and feed-in of a DCES. By normalizing both factors, operation of different DCES concepts and scenarios regarding their flexibility can be compared. The developed quantification method is applied in a case study of a hospitals' DCES in Germany. Using a MILP optimization model with different technology concepts and scenarios, we study FDI variation for a fixed tariff, a dynamic tariff and a CO_2-emission-optimized operation. The results of the case study prove that high-capacity combined heat and power units combined with thermal storage units lead to high flexibility provision. Also, the results outline higher flexibility provision in the winter than in the summer period.

Keywords:

Distributed cross-sectoral energy system; Flexibility; Optimized operation; Quantification indicator; Residual load.

1. Introduction and motivation

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

According to [1] flexibility demand results from the difference of electricity power consumption P_{el} and the renewable energy (RE) generation P_{RE} indicated by the residual load (RL) P_{RL} in (1).

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

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 ([2, 3]). However, with the phasing out of coal and nuclear electricity generation [§ 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 ([4, 5]).

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

Pina et al. [6] 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 (DCES) when they serve as local energy systems. DCES are primarily deployed in industrial, district, and building facilities with high energy demands, such as hospitals, swimming pools, universities, and shopping centers.

DCES primarily serve the energy demand of their respective facilities. Any surplus capacity can be provided to the higher-level energy system. However, since the availability of this capacity is time-dependent due to

 https://doi.org/10.52202/069564-0300

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 1.1.. Based on this, we define flexibility of a DCES in 1.2.. We show a literature review giving an overview of existing quantification methods in 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 2.1. and deduce and introduce it in 2.2.. In section 2.3., we present a case study in which we performe a plaubility check of the quantification indicator and in 3., we present the results of the case study. In 4., we conclude our results of the study.

1.1. Flexibility in the energy system

In [7–10], 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. Load-shifting is a technical implementation to offer this flexibility. Negative load-shifting is characterized by the reduction of electricity generation, increase of load and charging of storage. Positive load-shifting is characterized by the increase of electricity generation, reduction of load and discharging of storage. 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. In Fig. 1 [11–14] show an overarching definition of these technologies and operating modes and allocate 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.

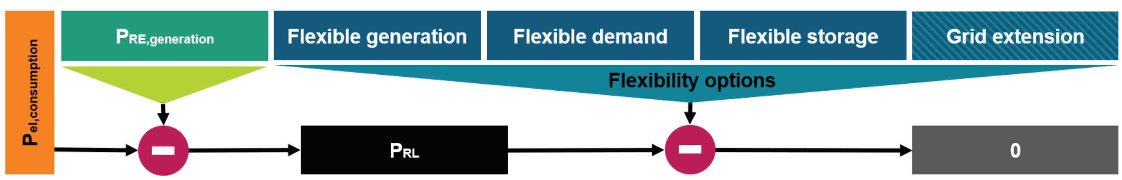

Figure 1: Fields of functions in an energy system with flexibility options covering RL. Figure in accordance with [15].

2. According to [16]], 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 of 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 prevention of bottlenecks. In Germany one instrument for providing grid-serving flexibility is e.g. ‘Redispatch’.
3. According to [10, 17], 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 consumers behavior. The consumer level can also be named *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 [18–20] the term *flexibility potential* is defined as the flexibility that a flexibility option can theoretically provide. [19] differentiates the flexibility potential into the terms technical potential, technically usable potential, socio-technical potential, economic potential and regulatory potential. [18] relates these potential terms to each other according to Fig. 2. In this logic, 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 selling flexibility services. 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.

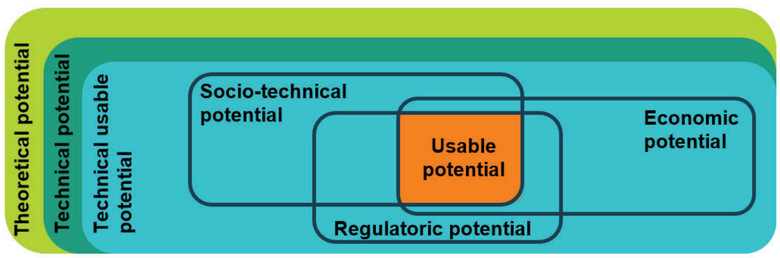

Figure 2: Classification of different flexibility potentials. Figure in accordance with [18].

1.2. Flexibility of a DCES

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 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 (TES). Every unit represents a flexibility option: The CHP unit, the gas boiler and the CC are flexible generators. The TES 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 [21], 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 define the flexibility understanding of the 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 service 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 DCES' facility energy demands are covered at any time. Dependent on the DCES' energy conversion technologies and storage units, the DCES operation covers RL in the higher-level energy system and thus, becomes a flexibility option.*

https://doi.org/10.52202/069564-0300

1.3. Review of flexibility indicators

To quantify the flexibility of DCES, several approaches can be found in literature. These approaches pursue different understandings of flexibility and pursue different flexibility objectives and result in a variety of indicators. However, none of these indicators allows to quantify the previously defined understanding of flexibility covering RL.

The existing indicators are valid for different time periods. Beginning with the quantification of points in time in [24, 26–29, 32], the period of the flexibility provision in [22, 23] and the quantification of a freely selectable period in [22,27,28,30,31,33,34]. The indicators also differ in the use of a reference operation or no reference operation in [22, 24, 26–29, 33, 34]. Based on the different approaches, also the number and types of used parameter varies. As in [22–24] only the time t of a flexibility provision is considered, in [22, 24, 26–29] also the power generation P is taken into account. In [22, 27, 28, 30, 31] both parameters of time and power are combined to quantify flexibility with a parameter of the unit energy E. In [27, 30–34] also external parameters of mostly cost signals and electricity prices are used. A distinction can also be made between relative result values in [24, 26, 27, 31, 33, 34] and absolute result values in [22, 23, 27–30, 32] with parameters of the units time, power, energy or costs.

The indicators from the literature can be categorized into indicators for time flexibility in [22–24], power flexibility in [22, 24–29], energy flexibility in [22, 27, 28, 30, 31], energy efficiency in [27, 28, 32] and the quantification of flexibility through external variables or signals in [27, 30, 31, 33, 34]. 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 also the higher-level energy system. Though, RL is not considered in any indicator.

2. Method

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

2.1. Requirements for a new quantification indicator

The new indicator is intended to quantify to which extend the market-serving flexibility of a DCES covers RL of the higher-level energy system. The indicator should enable a quantification of the usable flexibility potential. The focus is on quantifying the concurrence of the DCES operation with the 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 which 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 DCES 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 also presents the results in an easily and meaningful way. Further, the indicator should work for different quantification periods (QP).

2.2. The flexibility deployment index

We develop the new quantification indicator *Flexibility Deployment Index* (FDI). It consist of different electrical parameters. We consider on the one hand the electrical load-shifting through the grid connection of the DCES to and from the higher-level energy system and on the other hand we consider the RL of the higher-level energy system. Therefore, we set the system boundary around all DCES units and consider the DCES as a black box.

We display 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 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 and minimum electricity flow in QP. The denominator is determined by a case distinction, depending on whether power is purchased or feed in. If power is fed in (positive numerator), the maximum power feed-in during the QP is used as denominator. If power is purchased (negative numerator), the maximum purchased power in the QP is used as denominator. The $F_{DCES,t}$ has a possible range from - 1 to + 1, in which - 1 represents the maximum possible flexibility potential from negative load-shifting. Conversely, + 1 represents the maximum possible flexibility potential from positive load-shifting.

$$F_{DCSE,t} = \frac{P_{in,t} - P_{pur,t}}{|P_{DCSE,max}|} \qquad \text{with } P_{DCSE,max} = \begin{cases} \max\limits_{t \in QP}(P_{in,t}) & \text{if } P_{in,t} - P_{pur,t} > 0 \\ \max\limits_{t \in QP}(P_{pur,t}) & \text{if } P_{in,t} - P_{pur,t} < 0 \end{cases} \tag{2}$$

We display the flexibility demand based on the RL of the higher-level energy system by the *Residual Load Factor* ($F_{RL,t}$). As can be seen in (3), 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 QP. For $P_{RL,max}$ we 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.

$$F_{RL,t} = \frac{P_{RL,t}}{|P_{RL,max}|} \qquad \text{with } P_{RL,max} = \begin{cases} \max\limits_{t \in QP}(P_{RL,t}) & \text{if } P_{RL,t} > 0 \\ \min\limits_{t \in QP}(P_{RL,t}) & \text{if } P_{RL,t} < 0 \end{cases} \tag{3}$$

As a typical DCES provides flexibility services predominantly in a kW or low MW range and the RL is to be classified in a high MW or GW range, normalizing the load-shifting and RL values allows appropriate comparison of the two values resulting in the *FDI*. The comparison of absolute values would lead to very small values, which would impede the comparability. Thereupon, the *FDI* in (4) puts the technical flexibility offer of a DCES $F_{DCES,t}$ and the flexibility demand of the higher-level energy system's RL $F_{RL,t}$ in relation to each other.

$$FDI_t = \begin{cases} 1 & \text{if } FDI_{k,t} > 1 \\ FDI_{k,t} & \text{if } 1 \leq FDI_{k,t} \leq -1 \\ -1 & \text{if } FDI_{k,t} < -1 \end{cases} \qquad \text{with } FDI_{k,t} = \frac{F_{DCSE,t}}{F_{RL,t}} = \frac{P_{in,t} - P_{pur,t}}{P_{DCSE,max}} \times \frac{P_{RL,max}}{P_{RL,t}} \tag{4}$$

A positive value indicates that the DCES load-shifting does support covering RL of the higher-level energy system and a value of + 1 corresponds to maximum possible RL coverage by the DCES. A negative value indicates that the DCES load-shifting does not support covering RL of the higher-level energy system and a value of - 1 corresponds to 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 $F_{DCES,t}$. For 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 (5) results in the *average Flexibility Deployment Index* $\overline{FDI}$. It shows the mean *FDI* over the QP resulting in a value between - 1 and + 1.

$$\overline{FDI} = \frac{\sum\limits_{t \in QP} FDI_t}{n_{QP}} \tag{5}$$

2.3. Case study

To apply the defined flexibility indicator, we carry out a case study for the DCES of a hospital in Hattingen, Germany. The hospital includes around 270 beds. Its heat consumption is 4239 MWh and its electricity consumption is 2457 MWh per year. To determine the operation of the DCES, we use a mixed integer linear programming (MILP) optimization model. We create the DCES model with our self-developed optimization tool ESyOpT, which is based on the Python optimization-modelling library Pyomo ([35]) and the open energy modelling framework oemof ([36]). With the mathematical solver Gurobi ([37]) we calculate 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. The demand data is obtained from measurements of the hospital.

We use two different energy system concepts of the DCES in three tariff scenarios. We perform the calculation for one year in a resolution of 15 minutes.

2.3.1. Demand time series

For the input demand time series, we use the electricity, heating and cooling demands of the hospital measured in [38]. The input demand data for one exemplary year has an electricity base load of about 250 kW and an electricity peak load of about 400 kW. The heating base load is about 350 kW in summer and about 650 kW in winter. Cooling is predominantly needed in summer. The cooling base load is around 35 kW at night. During the day the demand rises to a peak of about 75 kW.

2.3.2. Energy system concepts

In the case study we consider two DCES concepts including a CHP, a gas boiler, an emergency cooler, a CC, a TES for heating and a TES for cooling. The unit interdependencies are analyzed in [38]. Depicted

https://doi.org/10.52202/069564-0300

in Table 1, we conceptualize one reference concept (*ref*) and one optimized concept (*opt*), which enables a flexible operation. The *ref* concept includes a CHP with an electrical nominal load of the electrical base load of the hospital. The *opt* concept includes 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 carry out the optimization for different tariffs. Depicted in Table 2, we use two electricity price tariffs and one tariff, which implies the CO_2 emission factor (EF). Furthermore, for the quantification with the FDI, we use an appropriate RL time series.

2.3.3.1 Optimization tariff scenarios

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

The *fix* tariff includes a fixed electricity price of 17.9 ct/kWh for electricity purchase and a revenue of 15.5 ct/kWh for electricity feed-in. We adjust the prices to the mean prices of the *dynamic* tariff to keep the same price level. The purchase and feed-in prices vary by taxes and levies.

The *dynamic* tariff includes the German intraday auction market price of 2021 (see Fig. 3a). The mean purchase price is 17.9 ct/kWh and the mean feed-in revenue is 15.5 ct/kWh. The volatility is 1.42 ct/kWh determined by the hourly standard deviation. The purchase and feed-in prices vary by taxes and levies.

The *EF* tariff includes the specific CO_2 emissions of the marginal power plant in the merit order in every time step by the approach of [39] (see Fig. 3a). We use data of [40–42] for the German electricity mix in 2021. Therefore, we use 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 is 1093 g_{CO_2}/kWh for lignite-fired power plants and the lowest EF is 0 g_{CO_2}/kWh for RE power plants. No EF for the electricity feed-in of the DCES is needed to calculate the optimized operation.

In all tariffs we use a fixed natural gas price of 3.77 ct/kWh with an EF of 201 g_{CO_2}/kWh ([40]).

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

2.3.3.2 Residual load time series

For calculating the FDI in every timestep, we require 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 use consumption and generation data from [43] for 2021. Figure 3b shows the composition of the average RL for the winter time, the summer time and for one year.

3. Results

We calculate the DCES' operation modes of the different concepts and scenarios and determine the FDI for each operation.

3.1. FDI dependency on unit operation and RL demand

We analyze 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

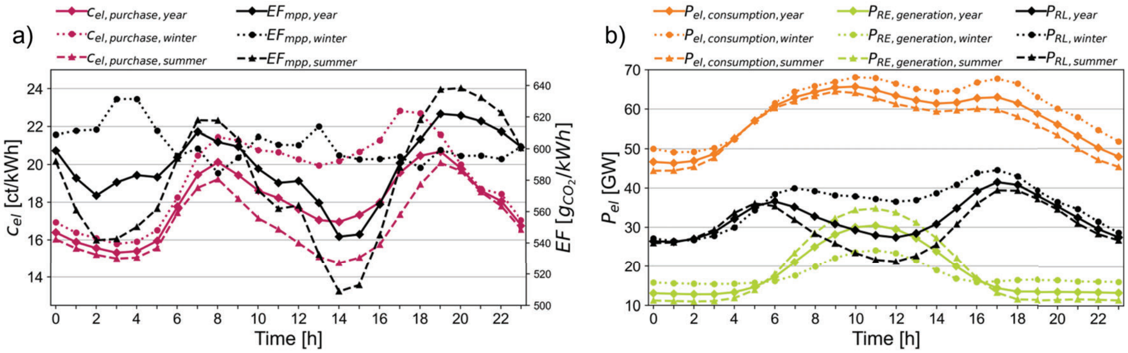

Figure 3: a) Hourly average electricity costs and hourly average EF. b) Composition of the hourly average RL.

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.

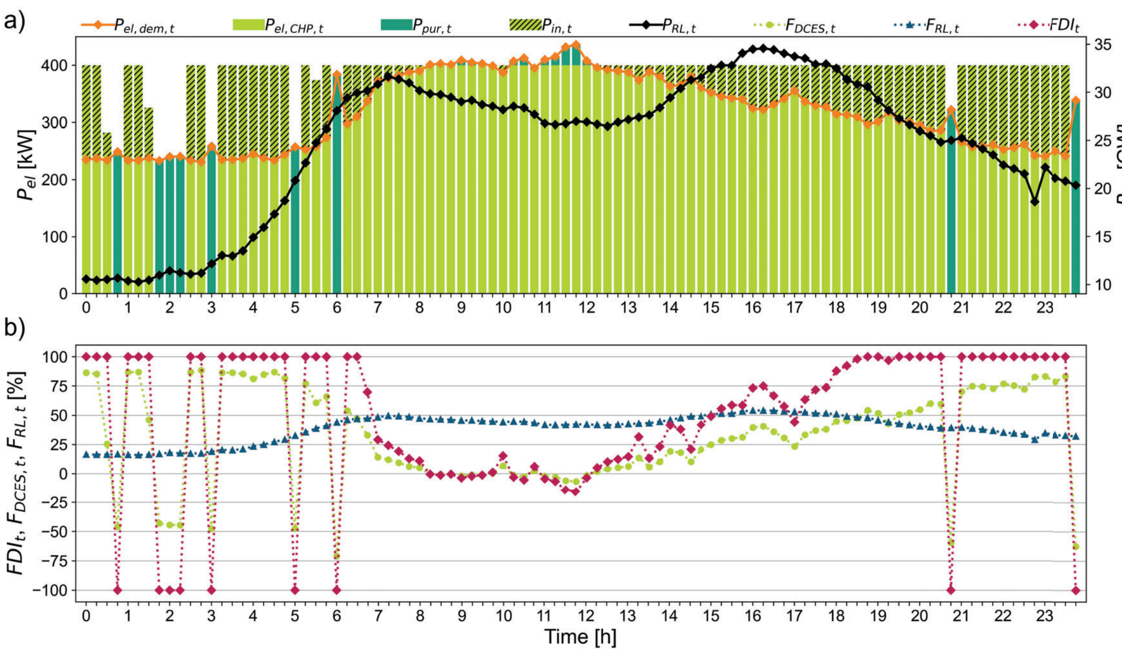

Figure 4: a) The DCES electrical key figures in quarter-hourly resolution of the *opt* concept in the *EF* tariff and the absolute RL for an exemplary day in winter. b) The corresponding $F_{DCES,t}$ and $F_{RL,t}$ for every time step result in the FDI_t.

Due to the high heat demand in winter, the CHP unit operates almost continuously at nominal load. But in some time steps, the CHP operation becomes restricted by the *EF* tariff optimization. This CHP restrictions result in additional electricity purchase. A detailed analysis of the DCES unit operation modes can be found in [38].

Table 3 shows the resulting values of the FDI_t for selected time steps. Among others, in the time steps at 04:00 am and 06:45 am 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 am or additional electricity purchase at 11:30 am, 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.

At 06:45 am, the DCES feeds electricity into the public grid and a positive RL exists in the higher-level energy system. This coherency supports covering RL. So, the FDI_t results in a positive value of 69.8%. At 04:00 am, 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%.

 https://doi.org/10.52202/069564-0300

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 am	- 45.9	16.7	- 100
04:00 am	81.2	23.4	100
06:45 am	33.0	47.3	69.8
11:30 am	- 5.9	41.9	- 14.1

A positive $F_{RL,t}$ and a negative $F_{DCES,t}$ result in a negative FDI_t. At 11:30 am, the RL is similar as at 06:45 am, but now the DCES purchases additional electricity from the grid resulting in more RL for the higher-level energy system. So, the FDI_t results in a negative value of - 14.1 %. At 00:45 am, 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

In Fig. 5 we calculate 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. So, 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 lower as the nominal load of the CHP. In most other cases, electricity is purchased as the demand is mostly higher 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 instead of reducing the RL.

The *opt* concept is useful to cover 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 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 [44] have proven a correlation between the RL and the electricity stock-market price in an energy-only-market, we have expected the highest $\overline{FDI}$ in the optimized operation modes regarding the *dynamic* tariff in every QP. Also, we have 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. Though, the $\overline{FDI}_{winter}$ is highest in the *fix* tariff. This gives an indication 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.

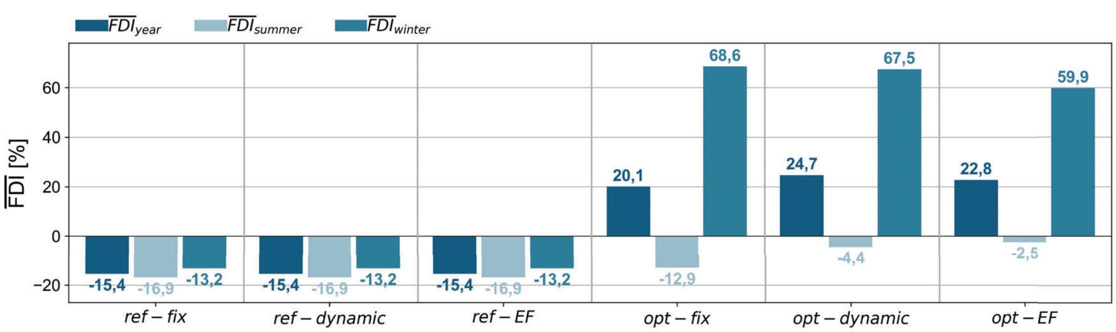

Figure 5: The FDI of relevant QPs for two concepts in three tariff scenarios. The $\overline{FDI}$ is presented for the QP of one year, summer time and winter time.

4. Conclusion and discussion

With the FDI we provide a new method to quantify the flexibility of DCES operation to cover RL of the higher-level energy system. As one element of power system transition 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 have outlined different understandings of flexibility and presented a specific definition for 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, respectively 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 DCES can be a flexibility option for covering RL in the higher-level energy system with an flexibility potential.

We demonstrated in a case study that regarding the supplied facility's demands and the DCES concept, the DCES might not have a high flexibility potential and therefore a low FDI when storage capacity and electricity generation are low. In this case, the FDI can only be increased by changing the DCES units or the facility's energy demand. We also studied the FDI of a DCES concept with high electricity generation and high storage capacity. In this case, the FDI was higher. As Pagnier and Jacquod [44] 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. Though, 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. Also, 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.

Unlike other flexibility indicators, the FDI allows 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 DCES of different facilities including different units (e. g. heat pump, absorption chiller etc.) and variations in capacity within the same higher-level energy system RL scenario. Though, in this study, the FDI was only applied for two DCES concepts of the same facility. Following the principle of the FDI quantification, the method might be adapted for even more energy applications interacting with the higher-level energy system. In this study the method was applied within an energy-only-market and the assertion of the results is directly connected to this kind of market design. Therefore, the presented quantification method needs to be proven in further studies for different DCES concepts, facilities, energy applications and market design.

In summary, the results of the case study show that a higher electricity generation capacity and bigger storage unit capacity in a DCES lead to a higher FDI. With the FDI we have developed an indicator to quantify the flexibility to cover RL regarding the higher-level energy system.

Acknowledgments

This research was supported by the German FEDERAL MINISTRY FOR ECONOMIC AFFAIRS AND CLIMATE ACTION. We thank our partners from STADTWERKE BOCHUM and AUGUSTA KLINIKEN BOCHUM HATTINGEN who provided data and expertise that assisted the research. We also thank our three reviewer for their great insights.

Nomenclature

Abbreviations

CC compression chiller

CHP combined heat and power unit

DCES decentral cross-sectoral energy system

DSM demand-side management

EF emission factor

MILP mixed integer linear programming

QP quantification period

RE renewable energies

https://doi.org/10.52202/069564-0300

RL residual load

TES thermal energy storage

Symbols

c costs, EUR

E electric energy, kWh

EF emission factor, g_{CO_2}/kWh

F_{DCES} flexibility potential factor, $-$

F_{RL} residual load factor, $-$

FDI flexibility deployment index, $-$

$\overline{FDI}$ average flexibility deployment index, $-$

P electric power, kW

n number of time steps, $-$

t time, h

Subscripts

dem demand

el electricity

in feed-in

mpp marginal power plant

pur purchase

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