Investigation of Cross-Sectoral Energy Concepts for Urban Districts Using Key Performance Indicators

Alexander Hobert, Michael Becker,
Tobias Müller, Markus Zdrallek
Institute of Electrical Power Systems Engineering,
University of Wuppertal,
Alexander.Hobert@Uni-Wuppertal.de

Dirk Aschenbrenner
WSW Netz GmbH
Wuppertal, Germany
Dirk.Aschenbrenner@WSW-Netz.de

***Abstract*— This paper presents an approach how cross-sectoral energy concepts in urban city districts can be evaluated with key performance indicators. For this purpose, the modelling of the different energy sectors and a demand response approach will be explained, that apply in this sectors with different load and feeder system like heat pumps or electric vehicles. Following the cross-sectoral key performance indicators will be demonstrated, divided in an ecological, economical and a grid operation aspect (e.g. the self-sufficiency or the mean carbon emission of the different sectors). In the last chapter, an urban district as objective of investigation will be used to evaluate, which sector is optimal for which aspect.**

***Index Terms:* urban energy system, cross sectoral energy concept, urban district, demand response, key performance indicator**

NOMENCLATURE

BESS	Battery energy storage system	CHP	Combined heat and power
DE	Distribution efficiency	DER	Distributed energy resource
DG	Distributed generator	DR	Demand response
EF	Emission factor	EV	Electrical vehicle
ESU	Energy system unit	HP	Electric heat pump
HS	Heat storage	IS	Incentive signal
KPI	Key performance indicator	MC	Marginal costs
OPF	Optimal power flow	PtH	Power to heat system
PV	Photovoltaic system	SF	Self-sufficiency
SoC	State of charge	UC	Use case
VPP	Virtual power plant		

EQUATIONS, PARAMETERS AND INDEX

$\vec{T}$	flexible electricity price tariffs	DER	local energy supply
$C_{EPEX,\,t}$	day ahead market prices	C_i	Cost of DER i
C_R	Regulated Costs	E_0	Energy before incentive
Δ	Adjusts variable	C_0	Cost before incentive
$w^i_{(s,\,e)}$	Power flow of a flexibility	$c^i_{(s,\,e)}$	Cost for a flexibility
T_t	Tariff for one time step	R_t	Residual load
CE_{Sector}	CO_2 emission for a sector	MC_{Sector}	Marginal cost for a sector
SF_{Sector}	Self-sufficiency for a sector		

I. INTRODUCTION

Within the context of the transition process of the German power system known as “Energiewende”, the energy system is currently restructured in terms of the type of loads, feed-in and geographical distribution of these units [1]. The next transition step will be the further installation of distributed energy resources (DER) – like photovoltaic systems (PV) – and distributed generators (DG) – like combined heat and power units (CHP) – in energy systems in urban districts. Additionally, new loads like electrical vehicles (EV) and power to heat systems (PtH) or energy storages like battery energy storage systems (BESS) will be installed. This process step induces the requierement for new concepts of supply and demand strategies, because a bidirectional energy flow is created. In the project “Virtual Power Plant” (VPP), such a strategy is developed for the energy supply and demand of an urban district in Wuppertal, Germany. This investigation uses the cellular approach [2] which aims at the local balancing of energy cells under use of different energy sectors (e.g. heat, mobility and electricity). In this research project the use of demand response (DR), the influence of sector coupling and local energy generation is investigated.

II. ENERGY CONCEPTS FOR AN URBAN DISTRICT

A. Definition of Flexibilities in the Urban Strucutres

A flexibility is defined as the adaptation of the demand or supply of an energy system unit (ESU) by an extern signal, with the aim to maintain the system stability or for cost effective manners [3]. The flexibilities in a district could be categorized into three sectors: heating, electricity and mobility. The different sectors include ESU such as BESS or electric heat pumps (HP) for flexible use of PV energy. ESU could be flexibility options when there has flexibility. The ESU and flexibilities in an urban district with a connection to the power grid are shown in Fig. 1. The energy can be shifted between the different sectors, which is possible through the sector couplers like HP or the charging station for EV. Not all ESU in an urban district can provide flexibility. [4]

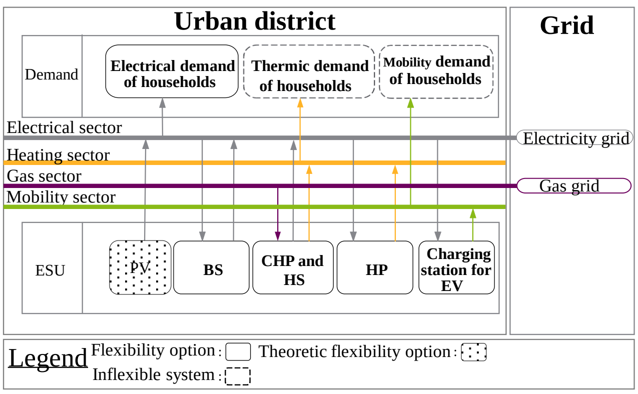

Figure 1. Cross-sectoral flexibilities in an urban district [4]

Therefore, are some systems marked as inflexible and other as theoretic flexible. Theoretically flexible means that any kind of flexibility is present, but the application is unlikely due to practicability, e.g. the chance of heat consumption. Therefore, are some systems marked as inflexible and other as theoretic flexible. Theoretically flexible means that any kind of flexibility is present, but the application is unlikely due to practicability, e.g. the chance of heat consumption. For this reason, theoretic flexibilities are not considered in this paper.

B. *Demand Response and Portfolio Optimization*

The electric grid of an urban district, like any other grid, needs a balance between supply and demand. For this reason, this chapter explains the simulation of DR as well as DR portfolio optimization. Furthermore, it will be described how the grid constraints will be considered. The aim is to reach an equalized energy balance at the low voltage level.

1) Demand Response System in an Urban District: An energy system that uses DR for the optimization of the grid operation requires an incentive signal (IS) for the loads and other flexibilities [5]. One approach to generate $\vec{IS}$ in a district is the use of flexible electricity tariffs T for consumers. For this used prive blocks caculate with equation (1) with a frequency of 15 minutes. The basis for this are the timedependet day-ahead market prices $C_{EPEX,t}$ which are a multiplied with the residual load R_t and the local energy supply $DER_{i,t}$ with its costs C_i as well as the taxes and incidental costs C_R. The frequency of 15 minutes is not fix another frequency e.g. with a dynamic distribution that sets new bounds for the time blocks (2).

$$\vec{T}_{Block} = \sum_{t=1}^{365}\left(\sum_{i=0}^{m} DER_{i,t}\cdot C_i + C_{R,i} + R_t\cdot\left(C_{EPEX,t} + C_{R,EPEX}\right)\right) \quad (1)$$

$$\vec{T}_{dynamic} = \frac{\sum_{i=0}^{k}\vec{T}_{Block,i}}{t_{end,i} - t_{begin,i}} \quad (2)$$

The time blocks show a correlation between market prices and local energy production. These correlations are shown in Fig. 2 as a heat map with the time of day on the abscissa and the month of the year on the ordinate with values between 0.18 EUR/kWh and 0.30 EUR/kWh. The annual and daily trends can be categorized into market effects and DER effects.

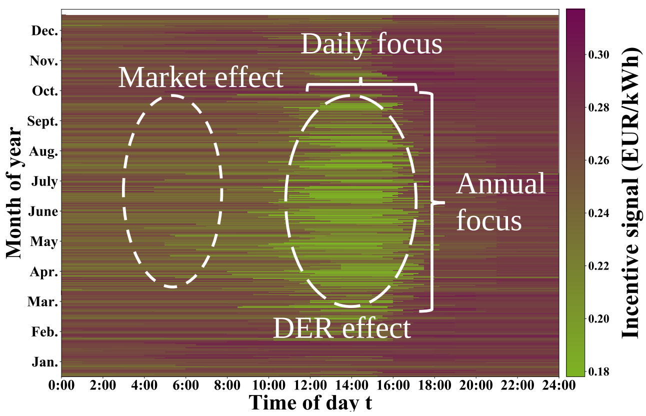

Figure 2. Yearly and daily pattern of cost blocks in the city district

Market effects can occur due to the increase of the supply by arbitrary resources or the decrease of the demand in the entire energy system. The DER effect is caused by the impact of the high production of PV energy in the district. This has a direct influence on the actual energy balance and in this model of the local prices. Because of this, the daily and annual trend towards the middle of the day can be explained by the high proportion of PV supply in the district.

2) Simulation of Demand Response: Flexibilities can be activated by DR. The use of flexibilities can be categorized into a direct and an indirect approach. The indirect approach means that the consumer receives the IS and shifts the energy consumption of household devices such as a dishwasher. Also a flexibility option without actuators. The direct effect means the use of flexibility is triggered automated by control of ESU such as sectoral couplers HP or charging stations. These two approaches are explained in the next two chapters.

a) Demand Response of indirect Flexibilities: A rational market participant can be modelled with different price elasticities ε, which can be used to describe how high the impact of an adjustment of a product price is. For consumers in the energy market, there are various hypotheses about price elasticity in the literature (3).

$$\varepsilon = \frac{\frac{\Delta E}{E_0}}{\frac{\Delta C}{C_0}} \Leftrightarrow \frac{\Delta E}{E_0} = \varepsilon\cdot\frac{\Delta C}{C_0} \quad (3)$$

It is defined as the relationship between price change and change of energy consumption in $\frac{EUR}{kWh}$. The price elasticity is different for each market participant.[6]. In this context E_0 describes the consumption of energy in time zero this mean the amount of energy before the incentive. C_0 is the price for the energy in the status quo. The change of both variables is indicated by the delta (Δ). Some examples for different price elasticities are illustrate in Fig. 3.

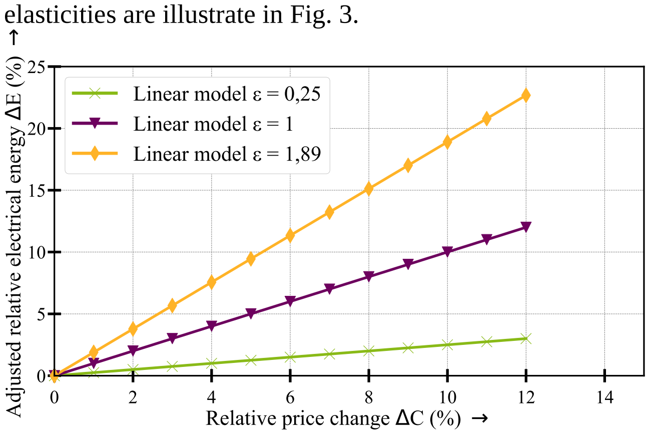

Figure 3. Price reaction models [6]

b) Optizimation of Direct Flexibilities: A linear optimization is used for the operation of direct flexibilities such as HP and EV. This optimization use the objective function (4) [7].

$$MIN\sum_{t=0}^{T}\left(\sum_{n=0}^{N} c_{t,n}\cdot P_{t,n}\cdot t\right) \quad (4)$$

This include the different flexibilities with their power flow $w_{(s,e)}^{i}$ and cost vectors $c_{(s,e)}^{i}$ which are multiplied with the period time $\tau = 15\ minutes$. The result of the objective is a unit commitment as timetables for the different flexibilities in the district. This is the minimized cost solution for the objective problem. This unit commitment includes only the constraints by the flexibilities like the maximum power or the state of charge (SoC) from storages. These constraints are considered in the plant model, illustrated in Fig. 4. However, the grid constraints considered in the grid model, which is discussed in the next section.

3) Simulation of the Grid State and Constraints: For the simulation of the grid constraints, which include the impact of the operation of the consumer and supplier on the voltage and asset utilization, a grid model is required. This model is a node and edge model which represents the grid assets such as lines and transformers. A time-based power flow in the grid is calculated, whereby the grid constraints are returned as a result in each time step (5).

$$\sum_{t=0}^{T} \min \sum_{i \in \text{Flexibilities}}^{N} P_{i,t} \cdot f_i\left(P_{i,t}\right) \qquad (5)$$

<u>With grid constraints</u>

$$\text{Edge: } V_{\min,i} \le V_{g,i} \le V_{\max,i} i \in \text{Edges}$$

$$\text{Lines: } L_{i,t} < L_{\max,i} i \in \text{Lines}$$

$$\text{Transformers: } L_{i,r} < L_{\max,i} i \in \text{Transformers}$$

This OPF calculates a valid grid state, generates minimum and maximum values for the flexibilities and transfers them to the plant model. The connection between the plant and the grid model is illustrated in Fig. 4 [8].

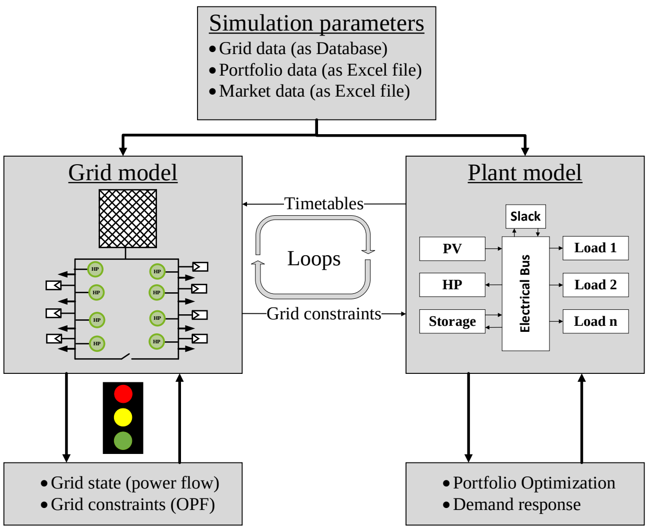

Figure 4. Plant and grid model [8]

C. Modelling of cross-sectoral Power Flows

The exchange between two energy sectors are represented by energy flows. This flow needs ESU which be able to link sectors (e.g. HP or a charging stations for EV), by converting the energy carrier to another energy carrier. Each sector represents an energy carrier that serves the desires of one or more demands in the districts. In Fig. 5, an example for a cross-sectoral energy system is illustrated.

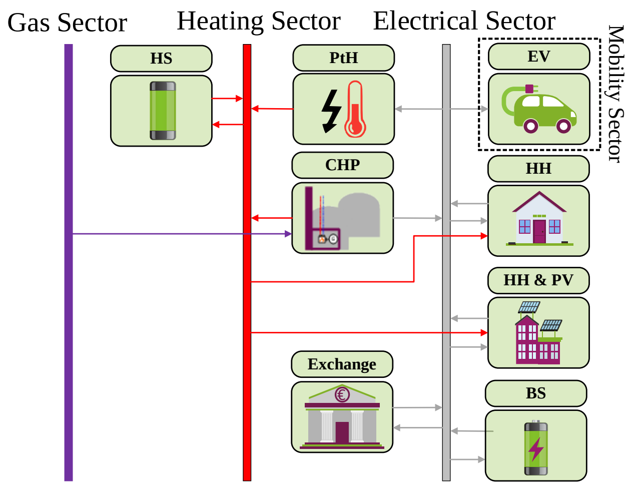

Figure 5. Cross-sectoral power flow model for city districts

On the base of this concept, a model is needed for the energy flows from the source to the sink of an energy demand, this model is illustrated in Fig. 6. The energy flow will be characterized by the power, the converting loss and a time series. This time series will be defined or optimized as a flexibility. Each power flow has marginal cost in EUR/kWh for the generation or conversion of energy. Storage units additionally require the parameter capacity. For the use of grid-based flexibilities, the minimal and maximal power parameters used for the range of adjustable power. If the boolean variable *Controllable* of flexible systems is "True", they have no predefined time series.

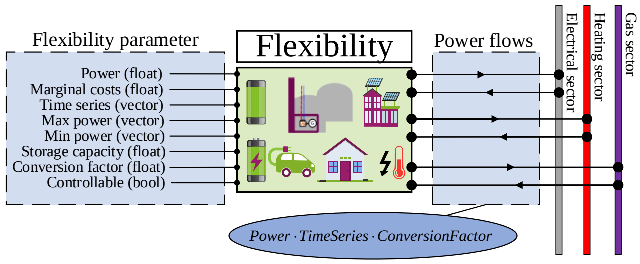

Figure 6. Cross-sectoral energy flexibility model

Each flexibility can have a connection to one or more sectors in both directions. In the illustrated example in Fig. 5., the BESS has a connection to the electrical sector in both directions and the HP has a connection to the electrical sector as a sink and to the heating sector as a source. An example for a load shifting with sectoral coupling (with PtHs case with HP and HS) is illustrated in Fig. 7. The HP converting electric energy in heating energy at times with a high amount of PV supply or with low day-ahead prices.

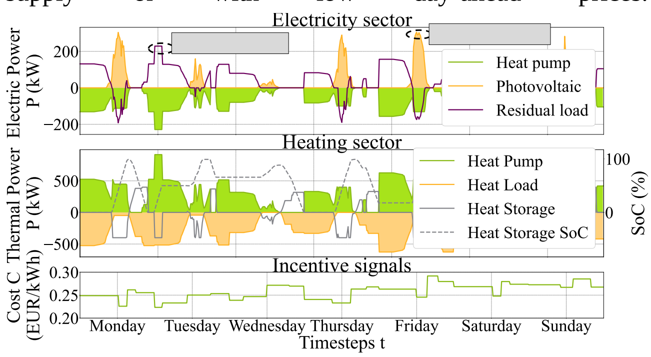

Figure 7. Cross sectoral load shifting in the heating sector

The HS stores the heating energy for the night hours. The SoC of the HS receives a PV bell-shaped curve caused by the HP working in the peaks of the PV feed. Another example for a cross-sectoral load shifting is by using flexibilities from the mobility sector with the charging process of EV. The flexibility can only be used while the EV is connected to the grid. With the IS the energy consumption will be shifted in the PV peaks. This application with 16 EV with a charging power of 11 kVA per EV and a PV over one week is illustrated in Fig. 8 in the first diagram. The second (middle) diagram shows the behavior of the EV over the week with driving and parking times. The EV time series of the driving behavior are based on a study which has investigated the statistic mobility behavior in Germany [9]. The third diagram (bottom) shows the IS for the load shifting. In comparison to the heating processes from Fig. 7, a significantly lower simultaneity is visible. The flexibility in the mobility sector has the same effect in combination with the IS. It leads to a load concentration in the PV peaks. This implies a reduction of the residual load from the city district.

Figure 8. Cross-sectoral load shifting in the mobility sector

III. Performance Monitoring of Energy Systems

A. Aspects for Key Performance Indicators

In order to investigate the operation of an urban district, different key performance indicators (KPI) are needed to represent the relevant areas of energy supply. These KPI are illustrated in Fig. 9. With the separation in the different aspects, the dependence between different issues of the energy supply in a complex system can be evaluated. The aspects are divided in an ecology part, for the impact of the environmental, in an economic part to investigate the financial status of the operation and in an operation part to investigate the technical aspects for the grid.

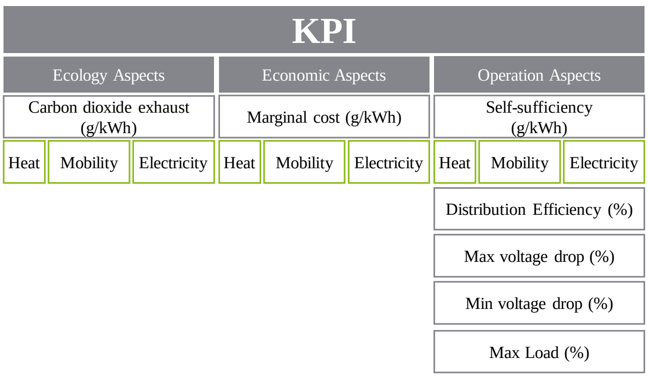

Figure 9. Key performance indicators for a cross-sectoral energy system

B. Ecology Aspects

For rating the ecology aspect need a KPI there are calculate the exhausts for the energy supply of the district. For this the means carbon dioxide exhaust for a specific sector CE_{Sector} (6) is used. The variable emission factor ($EF_{n,t}$) is depended on the time step t and the ESU n with the power flow $P_{n,t}$. The time dependency is due to the fact that the proportion of carbon dioxide in the electricity mix varies.

$$CE_{Sector} = \sum_{t=0}^{T}\sum_{n=0}^{N} \frac{EF_{n,t} \cdot P_{n,t} \cdot 15\,\text{min}}{P_{n,t} \cdot 15\,\text{min}} \quad (6)$$

C. Economic Aspects

The rating from the economic aspects done for financial effects, therefore the mean marginal cost for consume an energy carrier in a specific sector MC_{Sector} (7) is used. The cost for consumption energy is dependent of the time due the tariff T_t in a specific time step.

$$MC_{Sector} = \sum_{t=0}^{T}\sum_{n=0}^{N} \frac{T_t \cdot P_{n,t} \cdot 15\,\text{min}}{P_{n,t} \cdot 15\,\text{min}} \quad (7)$$

D. Operation Aspects

The aspect operation has a view on the condition of the grid and the impact of the use cases on the grid. A KPI to rate the autonomy is the SF of a specific sector SF_{Sector} (8). Energy flows are defined in this paper as self-generated when the primary energy has not been flowed through the power transformer station from the local grid. The variable $P_{Cover,t}$ describes the positive power flow through the power station. This will be multiplied with the fraction of the sector energy of the time step for each time step over the simulation duration.

$$SF_{Sector} = \sum_{t=0}^{T} 1 - \frac{P_{Cover,t} \cdot \frac{P_{Sector,t}}{P_{Heat,t} + P_{Household,t} + P_{EV,t}}}{P_{Sector,t}} \cdot 100 \quad (8)$$

For the investigation of limit violations in the grid a KPI for voltage and load in the grid assets is needed. The maximal and minimal voltage calculate from the simulation results the voltage rises and drops. The voltage fluctuations must be kept within the limits between -5 % and +5 % (9) (10). This investigation is performed for each node or line n and every time step t. The maximal current (11) calculates the status of the grid assets to investigate if there is no thermal overload of assets.

$$U_{max} = \max\left(\begin{bmatrix} U_{n=0,t=0} & U_{n=0,t=1} & U_{n=0,t=T} \\ U_{n=1,t=0} & U_{n=1,t=1} & U_{n=1,t=T} \\ U_{n=N,t=0} & U_{n=N,t=1} & U_{n=N,t=T} \end{bmatrix}\right) \quad (9)$$

$$U_{min} = \min\left(\begin{bmatrix} U_{n=0,t=0} & U_{n=0,t=1} & U_{n=0,t=T} \\ U_{n=1,t=0} & U_{n=1,t=1} & U_{n=1,t=T} \\ U_{n=N,t=0} & U_{n=N,t=1} & U_{n=N,t=T} \end{bmatrix}\right) \quad (10)$$

$$I_{max} = \max\left(\begin{bmatrix} |I_{n=0,t=0}| & |I_{n=0,t=1}| & |I_{n=0,t=T}| \\ |I_{n=1,t=0}| & |I_{n=1,t=1}| & |I_{n=1,t=T}| \\ |I_{n=N,t=0}| & |I_{n=N,t=1}| & |I_{n=N,t=T}| \end{bmatrix}\right) \quad (11)$$

The distribution efficiency (DE) is a measurement for the efficiency of the electrical grid and evaluates in which intensity the generated energy has been used (12). This depends on the local loss of energy through the grid assets and the operation point of the energy system with loads and feeders.

$$DE = \frac{\sum_{n=0}^{N} P_{load,n}}{P_{Loss} + \sum_{n=0}^{N} \left| P_{load,n} \right|} \cdot 100 \qquad (12)$$

This can be calculated by the ratio between consumed energy and the complete needed energy in the district and the sum with the loss power for each time step.

IV. Investigation of an Urban City District

A. Demand Response Use Case for an urban city district

In Fig. 10 the low-voltage grid of the investigated urban district is illustrated. This district has in the status quo 19 private buildings and one commercial building (No. 17). The district currently has no PV or usable flexibilities. It is fed from the higher voltage level (10 kV) with a 400 kVA transformer.

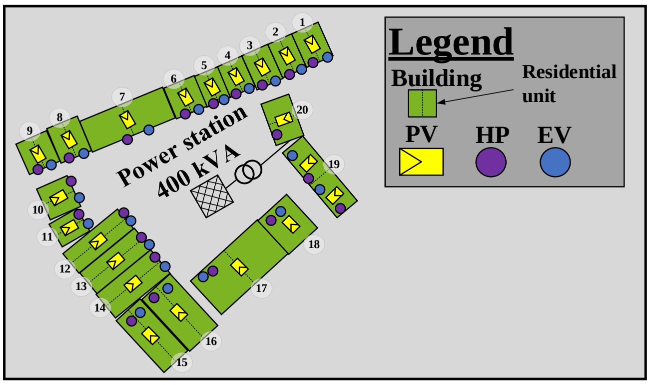

Figure 10. Low-voltage grid of urban city district

The different use cases to analyze the sector specific flexibility are illustrated in TABLE I. The use cases are simulated for a time horizon of three standard weeks. The base case represents the status quo of the district, this means without PV, HP or EV only the conventional household loads. UC I considers the installation of PV, HP and charging stations for EV as normal loads without DR. The PV potential is about 308 kVA with a $\cos_{PV}(\varphi) = 0.95$. At UC II the conventional household loads (e.g. dishwasher) are used as flexibilities. In UC III the flexibility of HP in combination with HS is considered. This concept is illustrated in Fig. 7. In UC IV the flexibility from the mobility sector with the EV charging is considered. This concept is illustrated in Fig. 8. The UC V combines the other use cases to one use case and shows flexibilization of the whole energy system in the district.

TABLE I. Use cases for the investigations

Use case	Description
Base case	Urban district in status quo (as reference)
UC I	Installation of PV, PtH, EV without DR
UC II	Use case I and DR for household applications
UC III	Use case I and PtH with DR
UC IV	Use case I and EV with DR
UC V	Combination of use case II, III and IV

B. Operation impacts of the Energy System

In Fig. 11 the KPIs for operation aspects in the different use cases are displayed. In the Base Case no limit violations in the grid occur. The DE is with 98.3 % in an acceptable range.

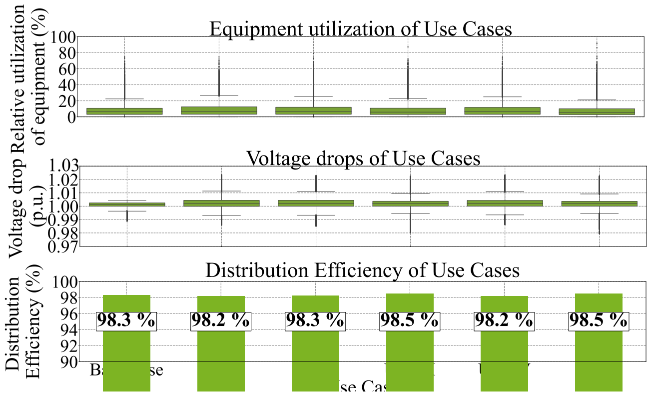

Figure 11. Key performance indicators for operation impacts (first utilization, second voltage, third distribution efficiency)

With the installing of the sector coupling systems in UC I an increase of the voltage drops occurs because the increasing of the installed load in the grid. The second visible effect is the decrease of the DE to 98.2 % because the loads consume energy outside of the PV curve. This increases the energy loss due the increased power flows over the power transformer station. This means, that the installation ofsector coupling systems without DR has a negative influence on the KPI of a district in the operating aspects due the increasing of the residual load in the grid. With a flexibilizations of the household application in UC II the DR increases to 98.3 %. A more significantly impact has UC III, with the flexibilisation of the PtH in the operation aspects with an increase from DE to 98.5 %. The UC IV with the EV has no impact on DE, it remains at 98.2 % in comparison to UC I. This is caused by the higher restrictions caused by the lower availability of electric vehicles compared to the PtH. On this basis, the charging process cannot be optimally shifted and it need more energy outside of the PV curve and a higher power flow over the power transformer station with more loss energy occurs. The best values can be identified at the use case UC V, here is the DE at 98.5 % and has a higher level in compare with Base Case. This effect can each explained with the effects from the load shifting, this increases the SF in the specific sectors. The SF of each sector at every use case is illustrated in Fig. 12. The base case has no SF because it has no DER installed in the grid, this means the complete energy have to flow through the power transformer station. The UC I have a SF for each sector. The SF for the electricity is 36 % and the mobility sector is the SF 35 %. On the heating sector has a small effect because the heating processes are only on the night and morning hours. In this time slots have not a significant PV feeding and almost the complete energy flow through the power transformer station. The complete SF for all sectors combined is 23 %. The flexibilisation of the household application in UC II has no significant influence, as the incentive to shift the loads in the household is not high enough and the installed power is too low. With the flexibilisation of the PtH in UC III the SF in the heat sector increases to 67 %. The other energy sectors remain largely stable at the same SF. In UC IV is an increase of the SF in the mobility sector to 67 % visible and the complete SF of all sectors is 34 %. The UC V companied all sectors, but no SF of 100 % can be achieved because the PV power cannot cover the complete demand in each sector due to the high energy demand of the EV and the HP. This means a significantly increase of the SF in one sector leads to a decrease the SF in another sector because the installed power of the DER limits the SF potential. This results in a negative correlation between the individual energy sectors. There a compromise must be found. This compromise must correspond to the supply tasks there are fixed by a utility.

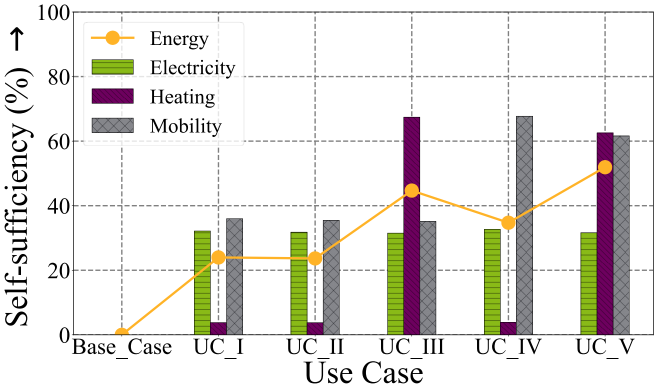

Figure 12. Key performance indicators for operation impacts (self-sufficiency)

C. *Analyze of Ecology Impacts of the Energy System*

The investigation of the influence for the ecology KPI due load shifting needed a carbon dioxide time series is needed. This has information to the time dependent emission factor in the power mix from the extern grid. This time series is calculated with the generated power of 2018 [10] and with different emission factors of the energy resources and the loss factors for storages [11–13]. The result of this analysis is illustrated in Fig. 13 as mean CE of the use cases. In the Base Case the electricity sector has a CE of 477 g/kWh. The mobility sector has an emission of the fossil fuels, this corresponds to 225 g/kWh. The heating sector is supplied with CHP and the emission is 250 g/kWh for the gas source. In UC I the CE decrease in the electricity sector on 352 g/kWh. The heating sector has an increase on 427 g/kWh. This is caused by the energy converting in the night and morning hours without a big DER fraction. The mobility sector has the same effect like the heating sector and the most charging processes are not in the low carbon time steps and is on 324 g/kWh.

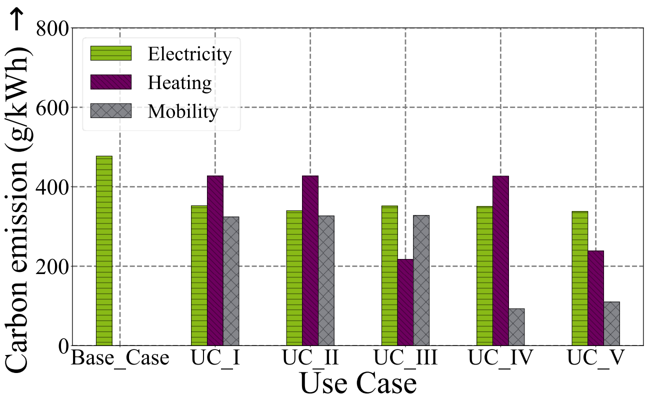

Figure 13. Key performance indicators for ecology impacts

With the DR approach in the other sector results a more significantly influence like in at the UC III, the CE decrease to 217 g/kWh, this is a reduction of half in the heating sector. The even greater potential for carbon reduction can be identified in the mobility sector in UC IV. The load shifting reduce the CE to 93 g/kWh. This results in a third of the original emission, compared to the UC I which use only static charging processes. The combination of each sectors in UC V has a significant reduction of the CE, but not to the complete potential can be achieved. Because the effect of the low carbon energy due the DER is not coverable in each sector. This means it is the same effect like with SF.

D. *Analyze of Economic Impacts of the Energy System*

For the effect on the MC the DR approach has a significantly price reduction effect in each sector (Fig. 14). At most this is identifiable in the UC III in the heating sector, the cost reduces from 0.25 EUR/kWh in the UC I to 0.14 EUR/kWh. The mobility sector can support by the DR too in the economic aspect, the MC in UC I is 0.25 EUR/kWh and it reduces to 0.20 EUR/kWh. The household applications can be reduced from 0.25 EUR/kWh to 0.18 EUR/kWh. In complete is a significantly cost reduction. The UC V combined the reductions in each sector and has a complete economic advantage.

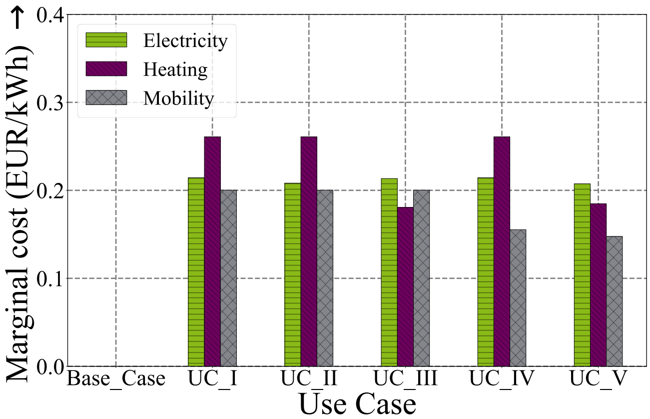

Figure 14. Key performance indicators for economic impacts

V. CONCLUSION AND OUTLOOK

This paper presents an approach for the increase of the flexible fraction of an urban energy system by considering a multi-energy carrier infrastructure and with sectoral coupling of the sectors heat, mobility and electricity. The flexibilities are implemented with a demand response approach, which uses flexible price incentives in the above-mentioned sectors. The second part of the paper present a key performance indicators methodology with three groups of them, where ecological, economical and operational aspects are considered. The methodology is applied on the investigation of an exemplary urban district in Wuppertal (Germany), where heat pumps, electric vehicles and photovoltaic systems are simulated in different use cases. This small influence also has an impact on the key figures for grid impacts. However, CO_2 emissions are reduced from 352 g/kWh to 339 g/kWh with DR. Similarly, the costs for energy supply are reduced from 0.21 EUR/kWh to 0.20 EUR/kWh. The cross-sectoral energy concepts with demand response have a more significant influence, the carbon emission in the mobility sector reduce from 324 g/kWh to 93 g/kWh. The same effect results in the heating sector, the reduction is from 427 g/kWh to 217 g/kWh. The financial influence is a reduction in the mobility sector from 0.25 EUR/kWh to 0.20 EUR/kWh. The heating sector at the same from 0.25 EUR/kWh to 0.14 EUR/kWh. The results show the most effect is in a sector coupled energy system and is important for a flexible city district.

References

[1] J.-F. Hake, W. Fischer, S. Venghaus und C. Weckenbrock, „The German Energiewende – History and status quo“ (German), *Energy*, Jg. 92, S. 532–546, Mai 2015, doi: 10.1016/j.energy.2015.04.027.

[2] T. Benz *et al.*, „The cellular Approach: The basis of successful, cross-regional energy transition“, VDE Verband der Elektrotechnik Elektronik Informationstechnik e. V. (VDE), Frankfurt am Main, Juni 2015. [Online]. Verfügbar unter: https://shop.vde.com/en/vde-study-the-cellular-approach.

[3] G. Papaefthymiou, K. Grave und K. Dragoon, „Flexibility options in electricity systems“, ECOFYS, Berlin, 2014. [Online]. Verfügbar unter: https://www.ourenergypolicy.org/wp-content/uploads/2014/06/Ecofys.pdf.

[4] Tobias Kornrumpf und Markus Zdrallek, *Analyzing Flexibility Options with Cross-Sectoral Requirements on Distribution Level*. Piscataway, NJ: IEEE, 2018. [Online]. Verfügbar unter: http://ieeexplore.ieee.org/servlet/opac?punumber=8540807

[5] M. Kaso, F. Musgens und O. Grothe, „Dynamic forecast combinations of improved individual forecasts for the prediction of wind energy“ in *2016 13th International Conference on the European Energy Market (EEM)*, Porto, Portugal, 2016, S. 1–5, doi: 10.1109/EEM.2016.7521228.

[6] P. R. Thimmapuram und J. Kim, „Consumers' Price Elasticity of Demand Modeling With Economic Effects on Electricity Markets Using an Agent-Based Model“, *IEEE Trans. Smart Grid*, Jg. 4, Nr. 1, S. 390–397, 2013, doi: 10.1109/TSG.2012.2234487.

[7] S. Hilpert *et al.*, „Addressing Energy System Modelling Challenges: The Contribution of the Open Energy Modelling Framework (oemof)“, 2017, doi: 10.20944/preprints201702.0055.v1.

[8] A. Hobert *et al.*, „Approach for multi criteria optimization and performance monitoring of a virtual power plant with urban structures“ in *Proceedings of the 25th International Conference on Electricity Distribution (CIRED 2019), Madrid (2019)*.

[9] Bundesministerium für Verkehr und digitale Infrastruktur, „Verkehr und Mobilität in Deutschland: - Daten und Fakten kompakt -“, Bundesministerium für Verkehr und digitale Infrastruktur, Bonn, Prognosen, Statistik und Sondererhebungen“, 2016. Zugriff am: 20. Dezember 2017.

[10] ENTSO-E, *ENTSO-E Transparency Platform*. [Online]. Verfügbar unter: https://transparency.entsoe.eu/dashboard/show (Zugriff am: 15. August 2019).

[11] V. Quaschning, *Regenerative Energiesysteme*. München: Carl Hanser Verlag GmbH & Co. KG, 2013.

[12] M. Sterner und I. Stadler, Hg., *Energiespeicher - Bedarf, Technologien, Integration*, 2. Aufl. Berlin, Heidelberg, s.l.: Springer Berlin Heidelberg, 2017. [Online]. Verfügbar unter: http://dx.doi.org/10.1007/978-3-662-48893-5

[13] A. K. Akella, R. P. Saini und M. P. Sharma, „Social, economical and environmental impacts of renewable energy systems“, *Renewable Energy*, Jg. 34, Nr. 2, S. 390–396, 2009, doi: 10.1016/j.renene.2008.05.002.