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Proposal of a regional grid cluster model for analysis of electrical power network performance

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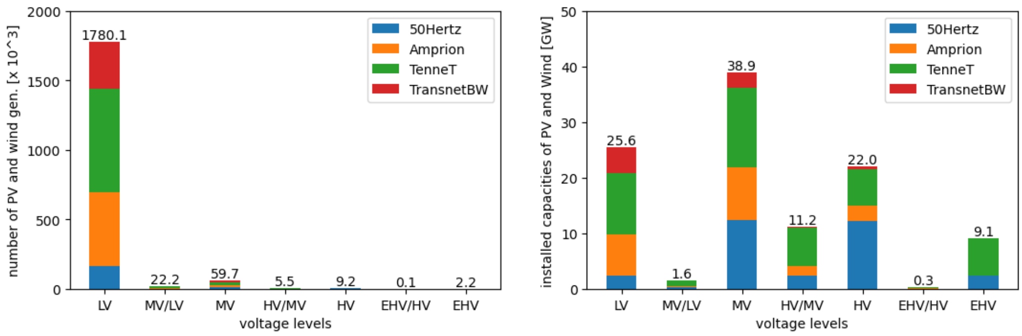
Abstract: This paper provides a method for simplified description of a regional power grid model aimed to deliver a grid reduction, and improve grid performance observability. The derived power grid model can be used to analyze the regional allocation of the decentralized energy generation and consumption. The expansion of wind and solar generation in the power system affects the residual load. The power balance between electricity consumption and generation was calculated and analyzed based on the temporal and spatial scales. The proposed grid clustering method is a useful approach for performance analysis in systems with a growing share of renewable generation.

Key words: decentralized generation, grid cluster, power balance, regional power grid

1. Introduction

In order to reduce greenhouse gas emissions, more and more penetration of renewable energies (REs) in power grids is to be carried out [1, 2]. With the massive expansion of decentralized energy systems in the electricity grid networks, primarily from wind generators and photovoltaic (PV) systems, the power supply system has been fundamentally changed, from central to decentral, from directional to bidirectional power supply [2]. In the past, the electricity from large central power plants was fed into the extra-high voltage level and through the transmission as well as distribution power grids transported to the consumer [3, 4]. Most renewable energy systems, on the contrast, are connected to the power grid at the lower voltage levels [5]. The integration of distributed energy resources in power systems brings new challenges because of their intermittent power generation, energy management and bidirectional power flows [6, 7]. Fig. 1 shows that the installed RE in four German transmission grid control zones up to 2019 are mainly connected to the voltage levels from low voltage (LV) to high voltage (HV) [5]. In addition to the German nuclear power plants being gradually decommissioned, the federal government of Germany decided in 2019 to phase out coal-fired power plants. The coal-fired power plants should be gradually shut down by 2038 at the latest [8–10]. Therefore, a significant portion of the energy supply must be covered by renewable energies in the near future [11]. The Four German transmission system operators (TSOs) have published a scenario framework for the network development plan (NEP) 2035, which will double the current installed capacities of renewable generation, especially wind and PV [11]. Three scenarios for the NEP were shown in Fig. 2.



(a) (b)

Fig. 1. Installed number (a) and capacities (b) of PV and Wind generators (data from [12])

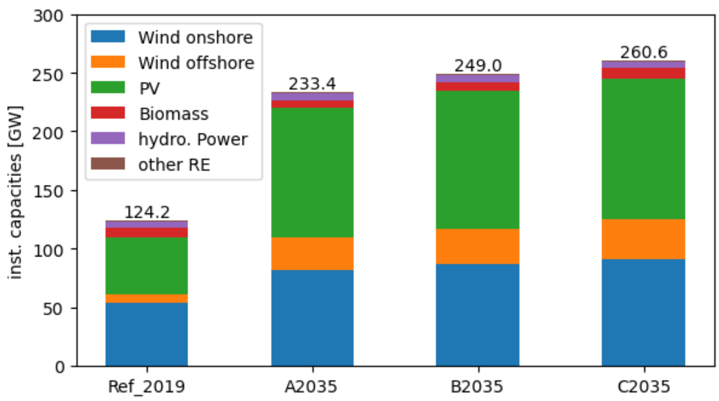


Fig. 2. Overview of the scenario's framework for the NEP 2035 (data from [11])

The share of electricity in renewable energies in gross electricity consumption in Germany has risen continuously since 1990. It rose from 3% in 1990 to 6.3% in 2000 and 17% in 2010 [13]. In 2019, 42.1% of gross electricity consumption was covered by renewable energy sources [14]. In some distribution network areas and even federal states, such as Brandenburg and Mecklenburg-Vorpommern in northeast Germany, the share of renewable energy in gross electricity consumption is now very high and even over 100 percent [13]. However, this does not mean the full supply of RE all the time in the power grid system. It is only the feed-in of extreme overproduction of RE electricity for some periods of time, such as days or weeks. The drastic change of the German electricity energy system with time-fluctuating power generation from RE brings new challenges and requirements to the stability and reliability of the power grids and the balance of power between electricity generation and consumption [10]. This is due to the fact that electrical power generation such as wind intensity and solar radiation energy rarely meets the demand for electricity [14]. In addition, the spatial distribution of the installed renewable energy system is highly dependent on the meteorological and geographical factors [16, 17].

A large set of power system model studies on a regional scale has received much attention and research in recent years, in order to analyze the mid- and long-term impacts of energy related policies [18, 19]. Current energy system models, which used grid reduction with the help of the method of Power Transfer Distribution Factors (PTDFs), focus on the operation points [20]. Urban energy modelling was presented in [18], with the static and dynamic characterization of power generation and energy consumption in one city. A GIS-based platform for the allocation and optimization of the distributed energy storage system was developed in [18, 21]. Small-scale modeling of current and future energy demand and electricity generation from renewable energies was built in [16, 17]. Large-scale integrated energy systems were presented in [22], the perspective of implementation was introduced and many examples of benchmark systems were used. The concept of an integrated energy system with sector couplings [23] and a multi-agent system for hybrid renewable energy sources were presented in [24–26]. The surplus power generation can be stored or transformed to other energy forms.

Regional analysis is very important to describe the regional difference in power supply and consumption, especially when focusing on weather-related renewable energies. A regional power grid model can be used to analyze how, where and when to convert and store electrical energy overproduction in comparison to local consumption. The integration of grids into large-scale energy system models is highly dependent on the model precision and calculation. However, current region-specific renewable potentials and grid reduction methods are mostly restricted to political administration borders or based on the national scales. There is no local clustering method when considering high-voltage substations. This paper contributes to the postcode and high voltage distribution network-based cluster model and analyzes the regional power generations and power flow parameters.

This paper is organized as follows. Section 2 describes the methodology of building a grid cluster model and considers the clustering of power grid data, which were used. Then the regional power balance between generation and consumption in a chosen cluster is observed. Section 3 presents the results of cluster related performance analysis, including allocation of renewable generation and power balance. Moreover, the relations of parameters for a cluster are reported and discussed. Conclusions and future works are given in Section 4.

2. Methodology and data

2.1. Cluster model of the electrical power grid

With regard to the voltage levels of equipment (e.g. lines and transformers), the power grids are generally divided into graded voltage levels [4], which enable the transmission and distribution of electrical energy. Based on the following hierarchical structure of the electrical energy system (Fig. 3) the entirety of all extra-high voltage (EHV) lines and associated equipment form the transmission network. The electricity networks at lower voltage levels together form the distribution networks. Large power plants feed on the transmission network and countless decentralized renewable energy systems transfer electricity into high, medium and low voltage networks, which is shown in Fig. 1.

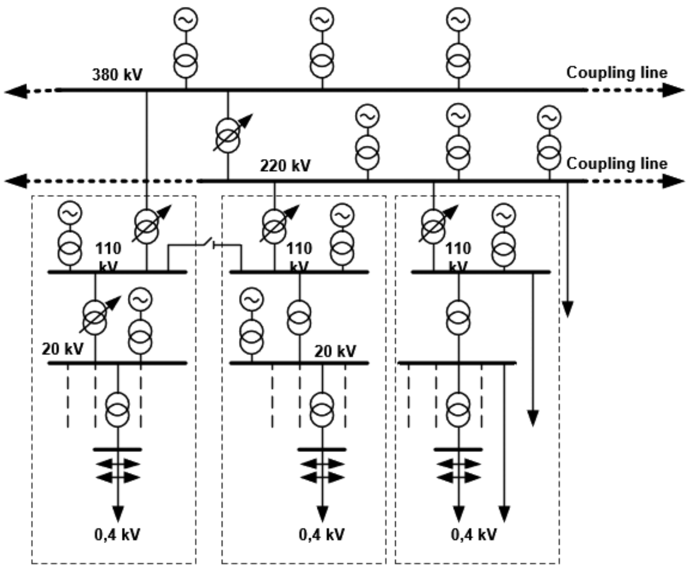
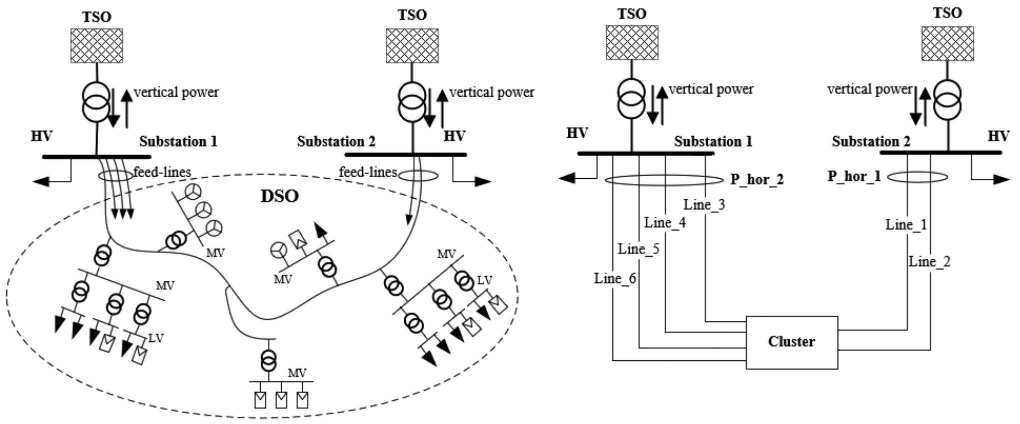


Fig. 3. Hierarchical structure of electrical energy system [4]

In order to reduce the complexity of the overall system and to analyze the effects of the decentralized power generation, a regional power system model is required. A simplified network structure is created at the connection points using the following reduction process. Firstly, the power grid was divided into zones according to the high voltage feed lines and then the internal connection lines were ignored. The area between the two transformer substations forms one power supply area, which can be called a network cluster in this paper. Within this network cluster there are different power suppliers and loads with different voltage levels. We can build one simplified circle under the distribution networks without considering physical topologies inside the area. We focus on the feed lines from both sides of the network cluster. For this purpose, the simplified network structure of an electrical energy system is drawn in Fig. 4. The transmission system operators and distribution system operators (DSOs) are connected with each other over the transformer substations.



(a) network topology (b) simplified network cluster

Fig. 4. Definition of network cluster model

As shown in Fig. 5, our studies use a variety of resource data, such as spatial data, measured data, and RE master data to form the regional cluster model. When partitioning the power grid into regional grid clusters the spatial dataset is required. By using OpenStreetMap (OSM) power relations and tags [19], the spatial data of high voltage lines, substations and boundary of postcode areas are downloaded and can be filtered according to the power tags.

The master data is archived from the market master data register (MaStR) [29], which is an official register of all systems and units in the German energy system and is managed by the German federal network agency. The installed capacities and energy forms are listed according to

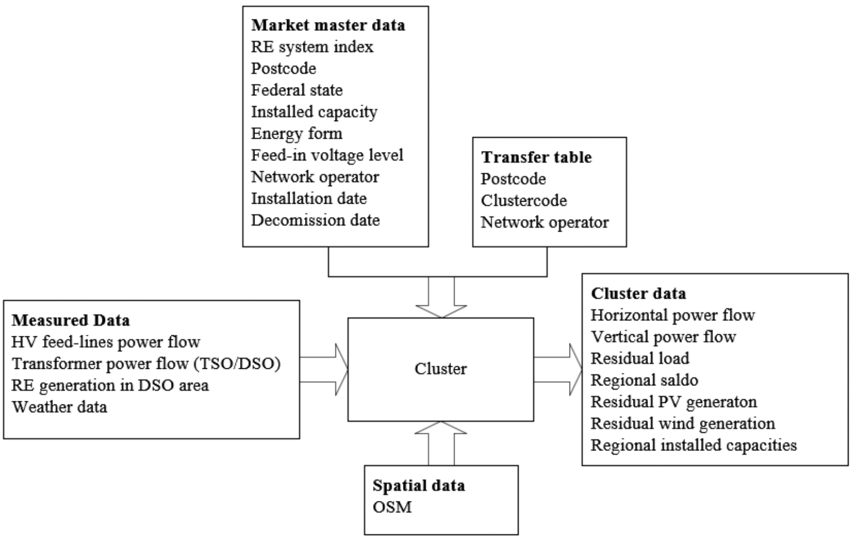


Fig. 5. Input and output concept of the cluster

their location information as postcodes and municipalities in the master dataset. The RE system index is a legally defined, unique identifier for the system, which the network operator assigned when the RE system was registered for the first time.

The transfer table, which includes the assignment of postcode areas to the cluster and relevant network operator, is used as a connector for the master dataset and spatial dataset. Based on the postcode, the RE system will be then assigned to different clusters. Through these postcodes the master data of RE and spatial data are combined with each other.

The measured data at substations and the generation data of RE were provided by regional high-voltage distribution system operators. Due to data protection, there is no access to the power generation and load of a single device. With the help of the historical electricity generation and high-voltage feed line power flows, the regional cluster generation and load are generated.

2.2. Cluster characteristics

The characterization of the different cluster power balance is based mainly on the regional generation and load. Besides the initial power generations, the network cluster was supplied from both sides of feed lines as well. Power flow through the feed-lines of substations can be measured using specially designated measuring devices. See the example in Fig. 4(b), there are 4 lines connected to the cluster on the left and two feed-in lines on the right. The aggregation of the power flow of the 4 left lines build one horizontal power flow for the considered cluster area and similarly the right lines form the second horizontal power flow for the cluster. This can be formed using Eq. (1). When we add the whole horizontal power flow, then we can get the balance of power flow for the cluster (see Eq. (2)), which is called power saldo here.

$$\text{Cluster\_}P\text{\_hor\_}j = \sum P\text{\_line\_}i\,, \tag{1}$$

$$\text{Cluster\_}P\text{\_saldo} = \sum \text{Cluster\_}P\text{\_hor\_}j\,. \tag{2}$$

Meanwhile, the balance of power flow for one cluster can be formed from Eq. (3), it describes the power difference between the electricity consumption and generation. So, the positive P_saldo means that, the electricity consumption is more than the power generation. More electrical energy should be delivered from outside to the cluster. While there is too much power generation over the consumption with a negative value of P_saldo, more powergeneration will be exported to the neighbor or to the superordinate grid network. The residual load is the proportion of the electricity load that is independent of the fluctuation energies [27]. For this reason, the residual load depends on two factors: the overall power load and fluctuating renewable energies supplied to the power grid. Here the fluctuation energy sources are mainly from PV and wind. The power generation from clusters at the distribution level is mainly from PV and wind, so power saldo can estimate the residual load very well.

$$\text{Cluster\_}P\text{\_saldo} = \text{Cluster\_}P\text{\_load} - \text{Cluster\_}P\text{\_generation}. \tag{3}$$

By comparing the local power generation and consumption, the good performances on peak-shaving and valley-filling have been highlighted [28]. In this paper percentile values were used to indicate the peak power from the power flow curve. For example, the quantile $q1$ is the value for which the percentile $p1$ of all values is smaller than this value, and the quantile $q2$ is the value for which percentiles (1 – $p2$) of all values are bigger than this value. By using Eqs. (4) and (5), we can calculate the quantity of percentile energy.

$$E_{\text{pos}} = \sum_{ti} (P_{ti} - q2) \cdot \Delta t, \tag{4}$$

$$E_{\text{neg}} = \sum_{ti} (P_{ti} - q1) \cdot \Delta t. \tag{5}$$

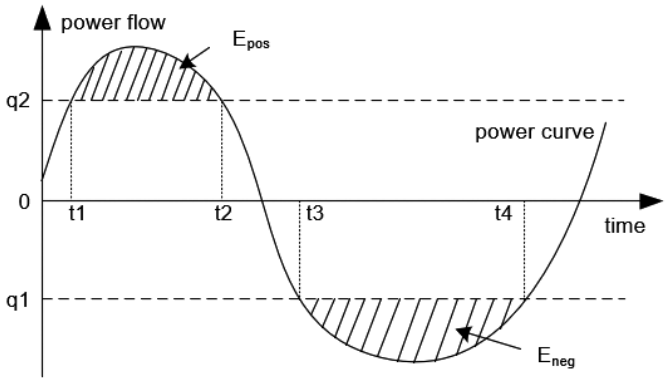


Fig. 6. Definition of percentile energy

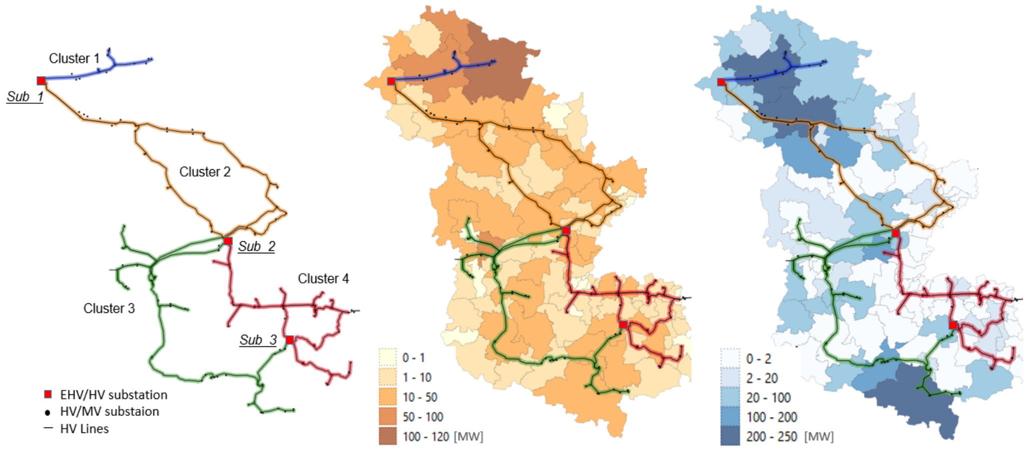
3. Results of cluster related performance analysis

3.1. Allocation of decentralized renewable generation

In this contribution, one regional high voltage subnet in west Brandenburg was taken as an example and was partitioned into 4 clusters. The regarded RE generators are connected to DSOs, whose voltage levels are from LV to HV. RE generators connected to the extra high voltage lines are not considered in this paper, because the reduced cluster model is based on regional HV lines and substations. The cluster partitioning with high-voltage grid lines and substations and the allocation of the installed PV and Wind up to year 2019 are showcased in Fig. 7, respectively. Based on the RE allocation the total installed capacities of PV and Wind in each cluster are calculated and shown in Table 1. Cluster 3 has the highest installed capacities in comparison to other clusters.

Table 1. Installed capacities of PV and Wind in clusters

	PV [MW]	**Wind [MW]**	**PV + Wind [MW]**
Cluster 1	245.8	404.3	650.1
Cluster 2	185.9	615.0	800.9
Cluster 3	364.5	731.7	1096.2
Cluster 4	108.4	129.5	237.9

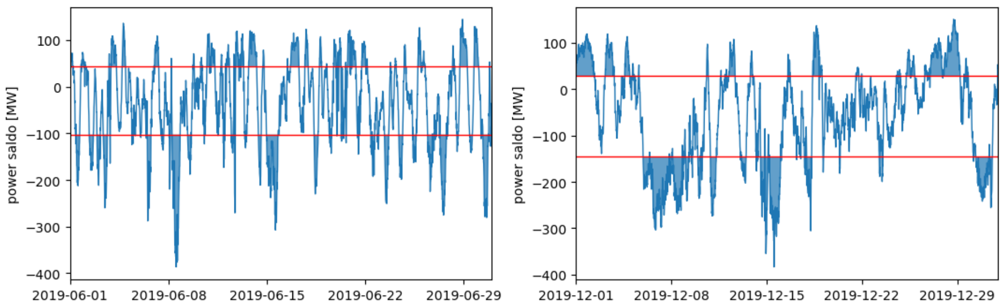


(a) (b) (c)

Fig. 7. Classification of clusters (a) and allocation of installed PV (b) and Wind (c)

3.2. Unbalance between load and generation power in a cluster

The difference power generation and consumption of cluster 3 is plotted in Fig. 8, where the power over quantile 75% and under quantile 25% are filled with color. It is clear that in June the power saldo fluctuates more frequently than in December due to the different contribution of PV and wind. When we focus on the colored area, which indicates the peak duration time of the power, winter has a longer duration time with a larger energy amount.



(a) June (b) December

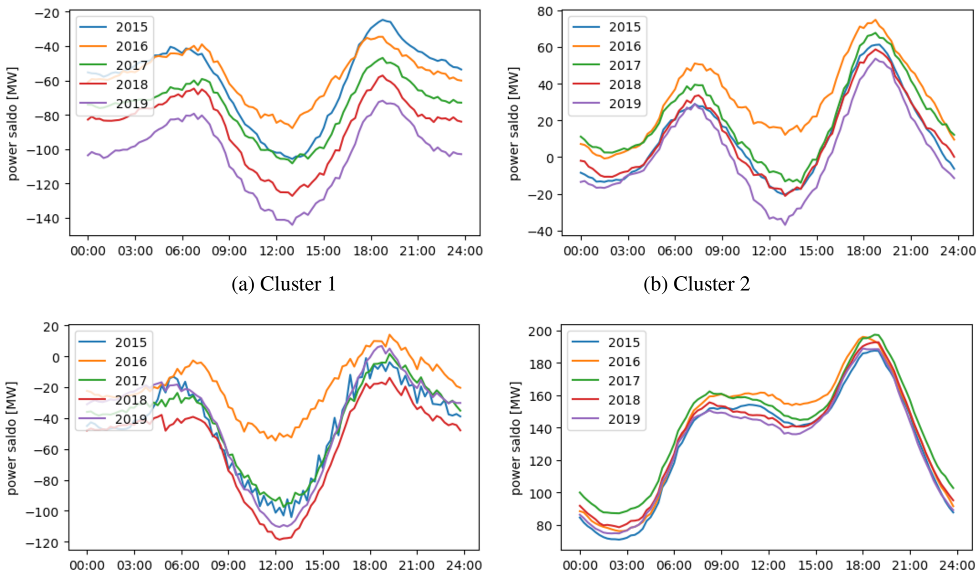
Fig. 8. Power curve of the saldo

Table 2 lists some results of the regional power balance parameters. The resulting demand and supply profiles can be used to investigate storage systems. With the reduced positive peak power means, the cluster needs less power supply from outside. The generation surplus (negative power saldo) can be stored locally in the regional network and then, due to the lack of electricity, the storage system can feed the power grid. Storage systems connected to the power grid can improve network operation and reduce the need for network expansion. December shows less frequency and a higher duration time than June. The maximal duration time bigger than quantile q_75 in June is about 14 hours and in December it lasts more than 1 day. The energy requirement E_pos in December is almost 3 times greater than in June.

Table 2. Results of the regional power balance

	June	**December**
peak pos. [MW]	144.6	150.6
peak neg. [MW]	–386.6	–383.4
E_pos. max [MWh]	710.5	1920.4
E_neg. max [MWh]	–2193.4	–2952.1
quantile q_75 [MW]	43.6	28.5
quantile q_25 [MW]	–101.7	–145.2
frequency (> q_75)	57	49
frequency (< q_25)	77	40
max. duration time (> q_75)	14 h 30 min	1 d 7 h 45 min
max. duration time (< q_25)	19 h 45 min	1 d 10 h 15 min

Fig. 9(a) to (d) illustrate the trend of annual average values of power saldo from different clusters focused on 24 hours. Compared with previous years the profile of power saldo moves



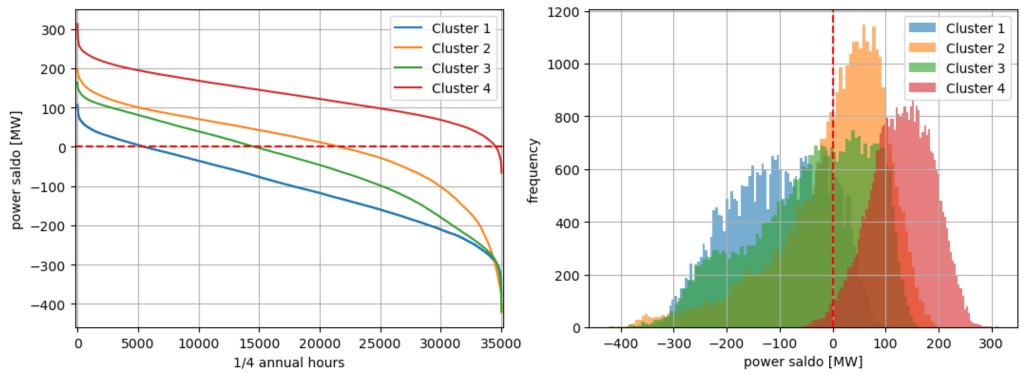
(a) Cluster 1 (b) Cluster 2

(c) Cluster 3 (d) Cluster 4

Fig. 9. Annual average of power saldo

downwards, due to the increased RE. The profile of cluster 4 differs from other clusters because of higher load consumption and installed sources of RE (see Fig. 10). Cluster 4 has the minimal value power at night from 2:00 to 3:00. The minimal values of cluster 1 to 3 are negative and occur mostly in the period of 12:00 to 13:00. It is clear that the profiles received at midnight and shown in Fig. 9(a) to (c) are higher in comparison to the profile in (d).

In addition, the annual duration line of power saldo in 2019 and the occurrence frequency are illustrated in Fig. 10. It can be seen that the maximal power saldo of cluster 4 is over 300 MW. A maximum of 100 to 200 MW is needed to compensate for the lack of electricity in clusters 1 to 3. Because of higher installed RE capacity, the power saldo reaches a minimal value of –400 MW, while the minimal power saldo for cluster 4 is only about –80 MW. The positive contribution in cluster 1 amounts to 40 GWh and approximately 930 GWh energy surplus was generated. The ratio between negative and positive energy amounts reaches 24. The ratio for cluster 3 amounts to 2.5 and for cluster 4 it is almost 0.



(a) (b)

Fig. 10. Annual duration profile (a) and frequency distribution (b) of the power saldo

3.3. Mutual relations of parameters characteristic for a cluster

The Pearson correlation coefficient of two parameters x and y, namely $\rho_{x,y}$, is a statistical index that describes the strength of the relationship between the two observed variables. It is defined as

$$\rho_{x,y} = \operatorname{corr}(x,y) = \frac{\sum_i \left[(x_i - \bar{x}) \cdot (y_i - \bar{y})\right]}{\sqrt{\sum_i (x_i - \bar{x})^2 \cdot \sum_i (y_i - \bar{y})^2}}, \tag{6}$$

where: x_i, y_i mean the variable value, $\bar{x}$, $\bar{y}$ mean the average value.

Fig. 11 presents the correlation coefficients of the power flow variables, which are derived from cluster 3, with 15-min temporal resolution data for 2019. It should be noted that the power generation summation of PV and wind (P_PV_plus_Wind) is more correlated with other variables than each individual power generation (P_PV or P_Wind). Especially power P_PV_plus_Wind

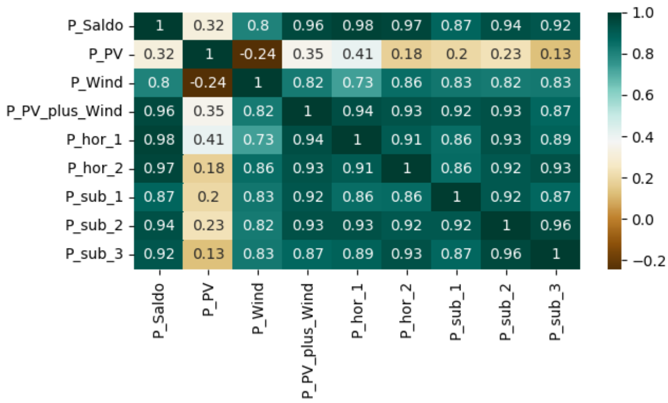


Fig. 11. Correlation coefficient of different variables of cluster 3

and power saldo (*P*_Saldo) are highly correlated. Furthermore, the two horizontal power flows have a high correlation coefficient with the power saldo. It is known that the possible power overproduction from PV and wind are delivered outside and fed back to the overlaid transmission grid. Therefore, it is clear that power *P*_PV_plus_Wind has a high correlation coefficient between horizontal power flows and vertical power flows at substations. Moreover, a high positive correlation exists among vertical power flows at different substations, which indicates a similar profile of the vertical power flows. The high related power parameters can be used in further studies for forecasting and filling missing measured data of clustered horizontal and vertical power flows. Renewable generation can be predicted with a high degree of probability from the measured data of horizontal and vertical power flows.

Table 3. Power flow parameters in cluster

Parameter	Meaning
*P*_Saldo	power difference between consumption and generation
*P*_PV	power generation from PV
*P*_Wind	power generation from wind
*P*_PV_plus_Wind	power generation aggregation from PV and wind
*P*_hor	horizontal power flow for cluster
*P*_sub	vertical power flow at substation

4. Conclusions and outlook

This paper gives a novel cluster-based approach to a reduced power grid model for the performance analysis of local power networks. The proposed cluster model refines grid clustering by building a network-oriented cluster at a high voltage distribution level, the cluster system enhances observability, avoids a single physical power grid element, and increases spatial resolution. The proposed cluster system connects the OSM spatial data, market master data and measured data. Moreover, this paper demonstrated the regional allocation of renewable generations. By using the horizontal power flows, the characteristic of cluster energy requirements (consumption and generations) and the extent of variability of power flows were then analyzed. It has been found that the power saldo between consumption and generation fluctuates more frequently in summer seasons, and winter seasons have a much longer peak duration time. The power profile from saldo differs due to the different contribution from PV and wind. With the high integration of renewable energies, the power saldo decreases gradually. The fluctuations result in negative efficiency and form the local electricity overproduction, which is transported to neighbor clusters or becomes vertical power that flows toward the overlaid voltage level. Furthermore, the correlation of characteristic power flow was then presented and compared. The horizontal, vertical power flows and power saldo are highly related. In future work, the highly correlated variables can be used for the possible stable operation between clusters and the prediction of related power flows. The cluster model can be applied in further studies for the operation and stabilization of the local energy storage.

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