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Urban-rural relations in renewable electric energy supply – the case of a German energy region

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ABSTRACT

So-called energy regions are one main driver in the transition towards 100% renewables on a local level. With their ambitious goals they strive for energy self-sufficiency based on their renewables potential. The model region consists of three municipalities (two rural regions and a medium-sized city) with the joint goal of 100% renewable electrical power supply in annual average by 2030. Based on the region's development path, this study predicts time-resolved renewable production and electrical demand profiles, including a sensitivity analysis on demand and generation profiles. In both rural regions renewable power production will exceed electrical demand while the city can only cover 27% of its power demand in 2030. The transition to renewable electricity supply of the city thus depends on its rural hinterlands. Synergetic cross-linking of urban and rural regions increases the total renewable electricity supply to 60 or 70%, depending on the size of the rural region considered. Seen from the perspective of rural regions cross-linkage to a city decreases the possible self-sufficiency compared to considering them as single regions. They can act as energy suppliers for neighbouring cities in the future.

Keywords:

Electric energy supply;
Urban-rural cooperation;
Energy regions;
Self-sufficiency;
Residual load

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1. Introduction

For the supply with raw materials and energy cities have always been dependent on their local surrounding areas or on regions which are located far away. Day and Hall [1] evaluate urban self-sufficiency as a myth, and in order to keep urban systems running, cities depend on *"large areas of productive ecosystems and waste sinks"*. Dosch and Porsche [2] argue that, in terms of a future climate neutral energy supply, urban territories might need even more support from their rural surroundings due to large land requirements for the installation of renewable energies.

On the other hand, the fight against climate change and the promotion of energy transition play a major role on a regional community level, and more and more strategies of how to mitigate greenhouse gas emissions are being worked out in urban and rural municipalities. In Germany and other European countries, the term "Energieregion (energy region)" has been established in the course of the energy system decentralization. This term is often used as a synonym for regions with the fixed political aim of a high percentage of renewables in energy supply up to energy autarky. Abegg [3] in a study on energy-autarchic regions in the European Alps speaks of a vision of regions to become independent from fossil energy imports. Numerous studies deal with the socio-economic factors of energy regions and their importance for the "Energiewende (energy transition)" (see e.g. [4-7]).

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In Germany, for example, initiatives like the "100% Erneuerbare-Energie-Regionen" (100% renewable energy regions) [8], the "bioenergy villages" [9,10] and the "Masterplan 100% Klimaschutz" (master plan 100% climate protection) [11] support regions which aim at a 100% renewable and regional energy supply. On the European level the "covenant of mayors" e.g. already represents more than 7,500 communities which plan to go beyond the 2020 and 2030 EU objectives in greenhouse gas emission reduction [12,13]. Mega cities like the Chinese City of Wuxi are also elaborating plans for a renewable energy transition [14].

In Germany, currently three of 153 100% renewable energy regions are urban-type regions [8]. However, the future energy demand for electricity, heat and mobility in cities cannot be covered sufficiently by urban territories alone. With increasing share of renewable energy sources (RES) in energy supply, cities become more and more reliant on their surrounding rural areas. In case of electric energy supply, cities can provide only little space for the installation of power supply units based on RES (RES-E) due to their high demand in residential, commercial and traffic areas. The available accounting for area restrictions is often defined as geographical potential (see e.g. [15]). Moreover, energy supply based on renewables requires significantly greater production areas than based on fossil fuel. If previously a great part of electric energy could have also been provided by fossil power plants within urban territory, this is not the case for renewables.

The use of wind energy in urban territory is often only possible as micro or roof mounted wind turbines. Not only does the problem of limited space in the urban environment have to be considered, but also wind conditions are not as intensive and often turbulent, thus horizontal axis wind turbines are not commonly used on roofs [16]. Many studies deal with those wind-flow patterns and turbulences in the urban environment and estimate the effects of urban morphology like roof shapes, building heights and neighborhood density on wind power yields (see e.g. [17-22]).

The costs of micro wind turbines are remarkably higher than big wind turbines with low yields. Besides, there are additional costs for approval procedures, noise and vibration protection. Installation solutions are also distinctly more specialized and not standardized as with photovoltaics. Grieser et al. [23] compare initial installation costs of three installations between 5,000 and 14,000 EUR/kW (in comparison: large onshore wind energy installation cost range from 1,000 to 1,500 EUR/kW, see for example current and past reports of IRENA [24], the Fraunhofer Institute for Solar Energy Systems ISE [25] and the German Institute for Economic Research [26]). They found small wind turbines, if at all, only profitable in coastal suburban or rural areas. Besides, comparison of installable capacity with large wind energy installations is still pending. Millward-Hopkins et al. [27] found 2,000 to 9,500 possible buildings to install small wind turbines in the British City of Leeds. Assuming an average power of 4 kW per micro wind turbine, the total installed capacity would match to maximum 38 MW, which corresponds to around 13 large wind turbines of 3 MW each which, however, could not be installed within the urban environment.

The solar potential in the urban environment is far higher than the potential of wind energy. Photovoltaics can primarily be implemented in cities on rooftops and facades. Prina et al. [28] e.g. only use photovoltaics as renewable energy producer with their maximum rooftop potential for their energy system analyses of an urban municipality in Italy. Miranda et al. [29] analyze the availability of rooftops to install photovoltaics by example of Brazilian municipalities. They found a much higher potential of installing photovoltaics in urban areas compared to rural ones. Since socio-economic factors like income were considered in the calculations of this study as well, e.g. the relatively higher income in Brazilian cities than in rural areas plays a role for the potential of photovoltaics to be installed. The urban density of buildings, however, is likewise emphasized in this study as a major factor regarding available rooftop areas for photovoltaics. Also, Mohajeri et al. [30] state a great potential of compact cities to install photovoltaics, but also indicate that the urban potential for rooftop and facade photovoltaics decreases with increasing building density. Brito et al. [31] investigate the potential of facade photovoltaics in various neighborhoods of the City of Lisbon, Portugal. In these latitudes and climate conditions façade photovoltaics have the potential to better meet the demand both in summer and winter.

Kurdgelashvili et al. [32], calculating a big potential of rooftop photovoltaics for a number of US-American states, point out that differences in the potentials between different states are not only caused by different irradiation ratios but also arise due to housing and rooftop characteristics. Changes of the solar potential on roofs and facades with increasing building density in cities due to shadowing and the calculation of the optimal orientation of neighborhoods is part of many studies (see e.g. [33,34]). Especially for neighborhoods to be newly built in the future, Sarralde et al. [35] propose an algorithm that calculates the optimal orientation of rooftops and facades for increase of the solar potential. New neighborhoods should not only be built energy-efficient, but also for harvesting solar energy. Lee et al. [36] also analyze the relation between housing density and *"the amount of solar irradiation that reaches a building"* and *"suggest ways to optimize the capacity for solar collection during the initial urban planning phase"*, and Morganti et al. [37] propose that those correlations *"should be integrated in the early stage of design process […] to guide strategies for harvesting solar energy and fostering solar energy technologies"*.

In contrast, rural districts usually own plenty of land in relation to their energy demand. Regarding the full potential of fluctuating RES, rural areas are more suitable. Here ground mounted photovoltaic plants and large, horizontal-axis wind turbines could be applied in the MW-range. Moreover, they are able to install more renewable energy plants than needed to cover their demand, which is why they become interesting with regard to the provision of energy for neighboring cities. But not only cities depend on their rural surroundings. Also, energy export regions might need an energy drain in times with high electric energy production from RES-E and low energy demand. Cross-linking rural and urban areas therefore seems appropriate for promoting a decentralized and regional renewables supply which also includes cities.

Current studies mainly focus on the evaluation of urban potentials for harvesting energy from renewables such as wind and photovoltaics power, biomass and geothermal energy. Very few scientific studies on the cooperation of cities and their hinterland exist. In case studies of cities examining the transition to renewables often possible supply through local hinterlands and RES-E located further afield is mainly discussed on a theoretical level, like for example by Droege [38], or calculations are based on annual energy balances like in the study of Grewal and Grewal [39] about the North American City of Cleveland. Also differences in e.g. energy consumption patterns or driving factors for CO_2 emission reduction between urban and rural areas are evaluated, as described in Ren et al. [40] for the Chinese case. Ren et al. analyze an urban-rural mutual cooperation to cover electricity and heat demand from the perspective of the Chinese urbanization processes and the development of low-carbon cities. The authors analyzed the cost and emissions minimum technology mixes for different scenarios with optimization algorithms and found the urban-rural cooperations to be the best option from economic and environmental viewpoints.

The research object of our study was the German master plan region Osnabrück-Steinfurt, located in the north-west of Germany. This region is funded by the project "Masterplan 100% Klimaschutz" (master plan 100% climate protection) [11] through the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) and consists of the two rural municipalities *Landkreis Osnabrück* and *Kreis Steinfurt* and the two cities *Osnabrück* and *Rheine*. The total region is characterized by the aim for greenhouse gas mitigation by 95% until 2050 compared to 1990, a fast extension of RES in the sectors electricity, heat and transport, and energetic self-sufficiency on an annual balance (for electricity supply in 2030 and for heat supply in 2050). The cities within this region are highly dependent on energy imports and cannot claim themselves energy regions as defined by energy autarky without their adjacent rural neighbors. As a first step, this study focuses on the region's development path for renewable electrical energy and performs load profile based self-sufficiency analyzes instead of annual balances. The further implementation of storages or other flexibility options are not considered.

In the medium-sized City of Osnabrück presented in our study the RES-E potentials within the city's territory clearly do not meet the annual electric energy demand. An urban-rural cooperation of the city with its two surrounding municipalities is most likely. Given that the city depends on cooperation with its rural surroundings when aiming at a full renewables supply, our study quantifies to what extent the city must rely on the neighboring rural energy potential. Further, the potential for providing the city with electric energy from the perspective of the two rural municipalities is investigated. Thus, the novelty of our study is the focus on urban-rural cooperation in the context of regional renewable supply with the aim for regional self-sufficiency. We focus on the electricity supply and the aim for self-sufficiency in this sector by 2030. Electricity demand also contains the demand in the heat and mobility sector which is directly supplied by power-to-heat and power-to-mobility.

The study is structured as follows: first we describe the methodology of transforming the annual values of the master plan targets for generation and demand to time step based profiles and of calculating the residual load. In section 3 we present results for deficit and excess energy and the resulting real self-sufficiency degrees of the three regions individually (3.1) compared to various cross-linking options (3.2). Further, in section 3.3 we investigate the influence of various generation and load profiles. In section 4 we close with a discussion of the results and a conclusion.

2. Methods

The model region Osnabrück-Steinfurt is located in the north-west of Germany and consists of two rural regions (Landkreis Osnabrück and Kreis Steinfurt) and one urban region, the City of Osnabrück, see Figure 1. The City of Rheine is not considered as a single region within this study. Although it has its own expansion scenario, it is part of the region Kreis Steinfurt and therefore not specified here. The three municipalities have defined a clear expansion path regarding the development of RE technologies for electricity supply (see Tables 1 and 2 for PV, wind power, and biogas potential). Table 3 gives the assumed electric energy demand pathway in the three municipalities. The expansion pathways as displayed in Tables 1 to 3 are based on a potential analysis made by the master plan regions in the context of developing their master plans (see [11] for general information about the master plan program, and the master plans for the City of Osnabrück [41], Landkreis Osnabrück [42] and Kreis Steinfurt [43]). Table 3 implements both, demand decrease by efficiency measures and an assumption of future electricity demand for heat, cold and mobility. The share of electric energy in the final energy demand thus increases.

In a first step of this study, the expansion scenarios for wind power and PV, the biogas potential and the assumptions of the annual electric energy demand were transferred into time-resolved electric energy feed-in and demand profiles to calculate self-sufficiency degrees and amounts of deficit and excess energy. When the integral of electrical deficit and excess energy profiles equals zero, mean annual self-sufficiency is reached, which is one of the goals of the considered Masterplan region. In reality, deficit and excess loads will either be

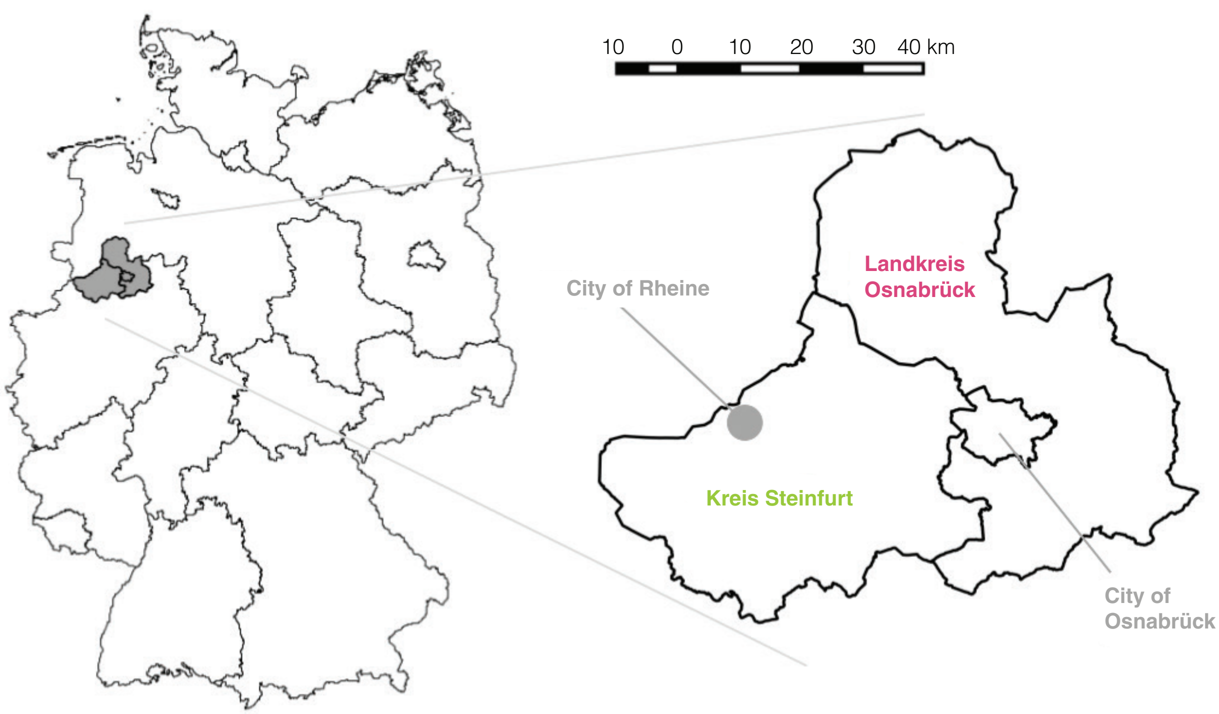

Figure 1: The master plan region Osnabrück-Steinfurt, consisting of two rural districts (Landkreis Osnabrück, Kreis Steinfurt) and two urban districts (City of Osnabrück, City of Rheine), and its location in Germany. The City of Rheine is part of Kreis Steinfurt and was not considered separately within this study

Table 1: Planned development of electricity supply from wind power and PV for the considered master plan regions and for the years 2020 to 2050. Numbers were taken from the potential analysis of the master plan regions [41,42,43].

	City of Osnabrück				Landkreis Osnabrück				Kreis Steinfurt			
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Installed wind power capacity [MW]	11	17	23	30	340	500	600	700	650	1000	1210	1470
Installed PV capacity [MW]	110	190	250	360	390	720	1050	1380	330	580	780	1130

Table 2: Planned development of electricity supply from biogas for the considered master plan regions and for the years 2020 to 2050. Numbers were taken from the potential analysis of the master plan regions [41,42,43]. To calculate the residual load biogas potential is transformed into electric energy using an electrical efficiency of 0.38.

	City of Osnabrück				Landkreis Osnabrück				Kreis Steinfurt			
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Annual chemical biogas potential [GWh/a]	40	50	70	80	720	730	740	740	740	1460	1140	1110

Table 3: Planned development of annual electric energy demand for the considered master plan regions and for the years 2020 to 2050. Numbers were taken from the potential analysis of the master plan regions [41,42,43].

	City of Osnabrück				Landkreis Osnabrück				Kreis Steinfurt			
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Annual electric energy demand [GWh/a]	930	910	900	880	1960	2000	2040	2100	2560	2260	2200	2120
Share of electric energy in final energy demand	20%	22%	25%	31%	22%	28%	38%	55%	24%	29%	41%	71%

exchanged with the grid or need to be leveled out by different flexibility options, e.g. battery storages, sector coupling, or smart energy systems.

Further, various urban-rural combinations were compared. All investigations are based on the conversion of annual values (consumption, potentials for bioenergy) and installed capacities (wind and photovoltaics) into time-resolved profiles with hourly time steps. To compare the different scenarios, the residual load (also called reduced load) was calculated by subtracting time step based generation profiles of fluctuating renewable electric energy supply from the likewise time step based load profile. The resulting reduced load profile gives information about energetic excesses and deficits.

The fluctuating RES-E considered in this study are wind power and photovoltaic (PV). Electric energy feed-in was derived by applying the *feedinlib toolbox* of the *open energy modelling framework (oemof)* [44]. Weather data (wind speed, solar irradiation; taken from [45,46]) were applied for the location of the City of Osnabrück (longitude: 8.0, latitude: 52.3). Primarily, the evaluations in this study are based on the weather year 2005. To cope with the sensitivity of weather data, the analysis concludes with a short assessment of the weather years 1998 to 2014 in section 3.3.

The region's master plans also identify the biogas potential for energy generation. In both rural municipalities a high number of biogas plants is in operation - mainly on manure and energy crops, but also on food-waste. The predominant operational model is constant combined heat and power (CHP) operation with parallel heat and electricity production. Within this study, the biogas plants are simplified regarded as constant electricity producers with an electrical efficiency of 0.38 (while in parallel producing thermal energy with an efficiency of approx. 0.4). Biogas supplements the supply from fluctuating RES-E as it can be used flexibly which should be the predominant operation mode in future. The total amount of produced electricity over the year is the same in constant or flexible operation mode. With respect to total electrical load profiles, flexible biogas plant operation will lead to lower deficit and excess load peaks and an overestimation of residual load.

By looking at Table 1 to 3 the different capabilities of renewable energy supply in urban and rural areas become obvious. While the planned development of wind energy, e.g., is up to nearly 1,500 MW in the rural municipality Kreis Steinfurt, the City of Osnabrück only holds a capability of 30 MW for wind power plants, which is 2% of the capability of Kreis Steinfurt and 4% of the capability of Landkreis Osnabrück. However, installing PV within the city is more promising than wind energy due to rooftop potential. Nevertheless, the overall space potential for PV is still less than within the rural regions since rural areas also offer space for ground-mounted PV systems. Furthermore, it is striking that the city's electricity demand is much lower than the demand of both rural regions. This is due to the different number of residents. The City of Osnabrück has around 162,000 residents whereas the Landkreis Osnabrück and the Kreis Steinfurt have more than twice as many residents, namely 358,000 and 443,000 respectively. Conversion into demand per resident results in the same dimensions (e.g. in 2030: City of Osnabrück: 5.6 MWh/ resident, Landkreis Osnabrück: 5.6 MWh/resident, Kreis Steinfurt: 5.1 MWh/resident).

By means of the curves of two weeks the electric energy generation from RES-E and the electric energy demand of the Landkreis Osnabrück is shown in Figure 2. The focus within this study was on two different load profiles scaled down to the annual demand of the particular region (see Table 3) and representing two extremes. Load profile 1 represents the German load profile of the European Network of Transmission System Operators for Electricity (ENTSO-E) [47] which can be seen as too smooth for a region whose residents account for only slightly more than 1% of the total residents in Germany. The second load profile is the standard load profile for households (H0) from the German Association of Energy and Water Industries (BDEW – Bundesverband der Energie- und Wasserwirtschaft) [48] and represents only around 400 households [49]. This load profile is

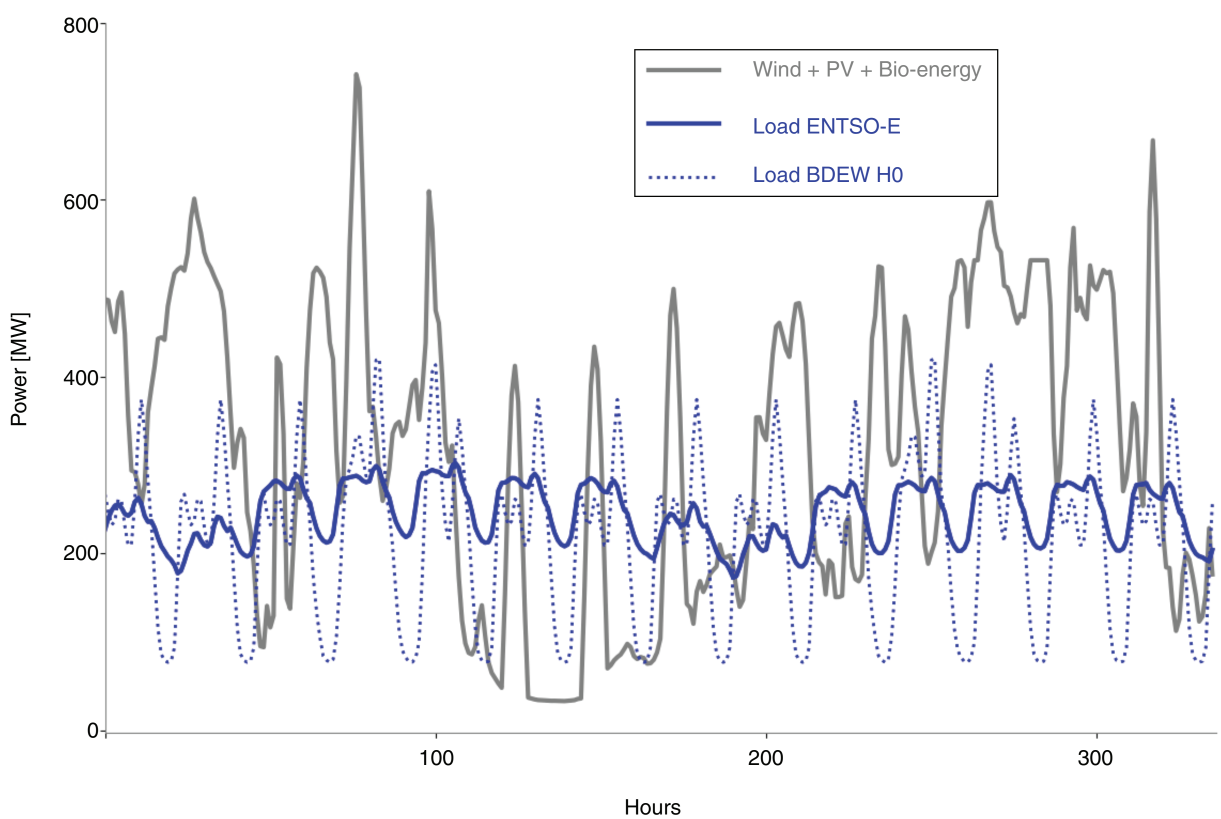

Figure 2: Electric energy generation from RES-E (wind power, PV and bio-energy), electric energy demand as ENTSO-E load profile (solid, data taken from [47]) and BDEW H0 load profile (dashed, data taken from [48]), calculated for Landkreis Osnabrück for two weeks; master plan scenario 2030, weather year 2005. Reduced load is calculated by subtracting electric energy generation from load profile

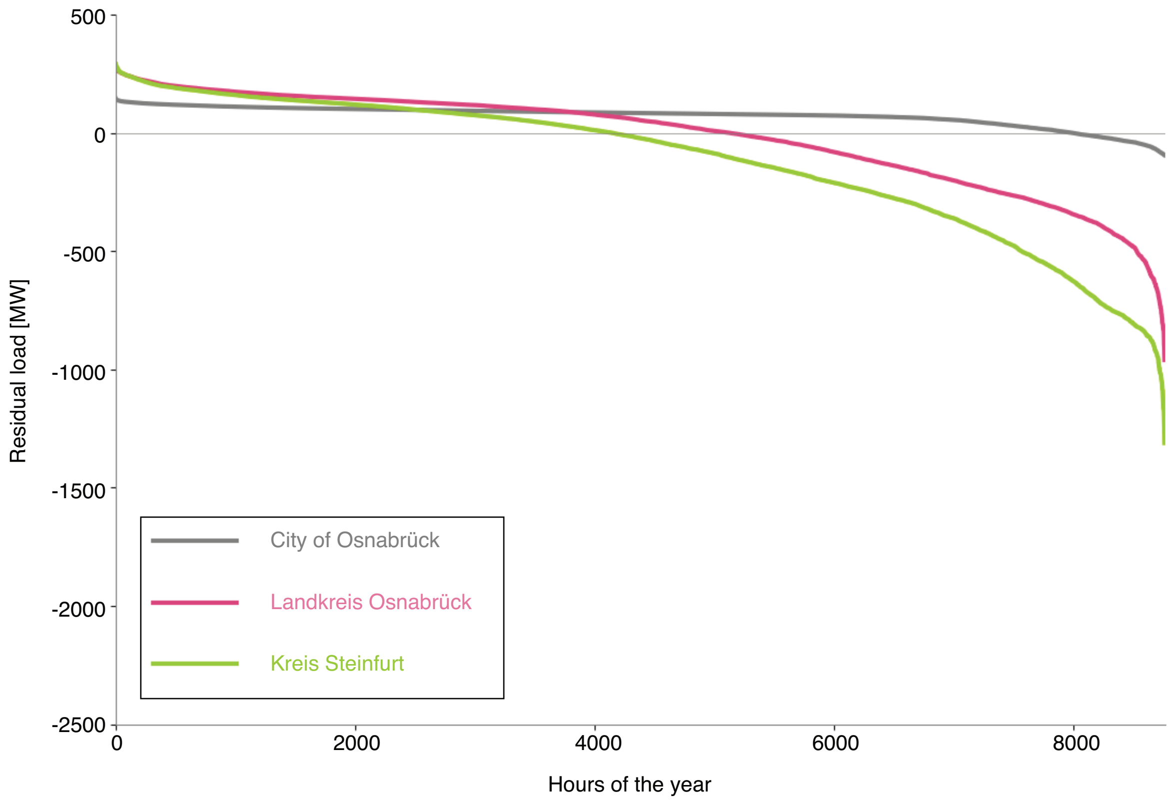

Figure 3: Annual load duration curve of the residual load (positive ordinate values: deficit, negative ordinate values: excess) in Landkreis Osnabrück, Kreis Steinfurt and the City of Osnabrück, calculated with weather data (wind speed and solar irradiation) of 2005 [45,46], models for wind power and PV feed-in [44], a simplified biogas electric energy model, master plan targets for 2030 (see Table 1 to 3) and ENTSO-E load profile [47]

originally given in 15 minute time steps and has been converted into hourly time steps by averaging over four quarters of an hour each. The influences of the different load profiles on the results are, just as the influence of different weather years, discussed in section 3.3. With Figure 2 the basic idea behind the residual load calculation is shown. Subtracting the RES-E generation profile (gray) from the load profile (blue) results in a time step based profile of positive and negative residual load which represents deficits and overproduction (see Figure 3 in the Results section).

3. Results

The following chapter presents the results of the residual load analysis for the three individual regions of the model region (3.1) and shows the effects on deficit and excess energy as well as real self-sufficiency degress when cross-linking urban and rural regions in various cross-linking options (3.2). Further to cope with the sensitivity of input data the influence of different weather data and load profiles has been analyzed (3.3).

3.1. Individual residual load of the three regions

Figure 3 shows the calculated annual load duration curve of the residual load for all three considered municipalities and the year 2030. Positive ordinate values reflect a deficit in demand coverage, negative ones an excess in electricity supply. The graph also depicts the number of hours with deficit or excess in energy supply and maximum values of the positive and negative residual load.

In 2030, all regions exhibit deficit times (positive ordinate values). In total, the deficit energy in the City of Osnabrück amounts to 670 GWh, in Landkreis Osnabrück to 640 GWh, and in Kreis Steinfurt to 480 GWh. With the city's demand of 913 GWh in 2030 and without implementation of energy storage, this results in a predicted deficit of 73% and thus a real self-sufficiency degree of 27%. At the same time, the real self-sufficiency without storage is 68% in Landkreis Osnabrück and 79% in Kreis Steinfurt.

The share of excess energy (negative ordinate values) compared to the annual demand is 69% in Kreis Steinfurt (1,550 to 2,260 GWh), 40% in Landkreis Osnabrück (800 to 2,000 GWh) and less than 3% in the City of Osnabrück (26 to 910 GWh)." (VALUES ADJUSTED ACCORDING TO TABLE 3)

. The excess energy in Kreis Steinfurt is thus far more than half of the annual demand, which is not the case in Landkreis Osnabrück. Landkreis Osnabrück produces only half of the excess energy of Kreis Steinfurt due to the installed wind power which is only half of that in Kreis Steinfurt (see Table 1).

Figure 4 shows the residual load as annual load duration curve for both rural regions, supplemented by the years 2020, 2040 and 2050. The deficit energy of Kreis Steinfurt still exceeds that of Landkreis Osnabrück in the year 2020 (1,010 GWh compared to 790 GWh), it decreases much faster though (until 2050 more than 60% to 360 GWh, compared to almost 30% decrease in Landkreis Osnabrück to 560 GWh). In Kreis Steinfurt, from 2030 on a deficit in electric energy supply results in less than half of the total hours of one year. In Landkreis Osnabrück, this is not the case before 2050.

The excess energy increases much faster than the deficit energy decreases over the considered period. In both rural regions the excess energy increases by a factor of six to seven (Kreis Steinfurt: from 480 to 3,030 GWh, Landkreis Osnabrück: from 270 to 1,790 GWh). The deficit energy of the City of Osnabrück (not shown) decreases likewise by almost 30% from 770 GWh in 2020 to 550 GWh in 2050; the excess energy increases to only 170 GWh in 2050. Times without deficit in energy demand in the City of Osnabrück are little: in the year 2020 there are only 80 hours without deficit in energy supply, which correlates to three days.

3.2 The benefit of cross-linking urban and rural areas

In the following, the potential of urban energy supply through rural regions is evaluated based on two different urban-rural-connections. The first connection combines the City of Osnabrück only with the rural municipality Landkreis Osnabrück. The second connection also considers the second rural municipality, Kreis Steinfurt, therefore representing the overall master plan region.

Figure 5 shows the monthly summary of demand (positive values) and excess energy (negative values) of the City of Osnabrück and the Landkreis Osnabrück as single regions before cross-linkage. Further the demand in the positive axis is subdivided into covered demand and deficit energy. It can be seen that the City of Osnabrück covers a part of its demand out of its own resources, especially in summer, however only by around 27%. The excess energy is only at around 26 GWh (see section 3.1). In the winter months, particularly in January, November and December, the energy supply conditions of the City of Osnabrück lead to zero overproduction.

The Landkreis Osnabrück, on the other hand, exhibits large amounts of excess energy in almost every month of the year. In January and March, but also in April and May, the excess is higher compared to the rest of the

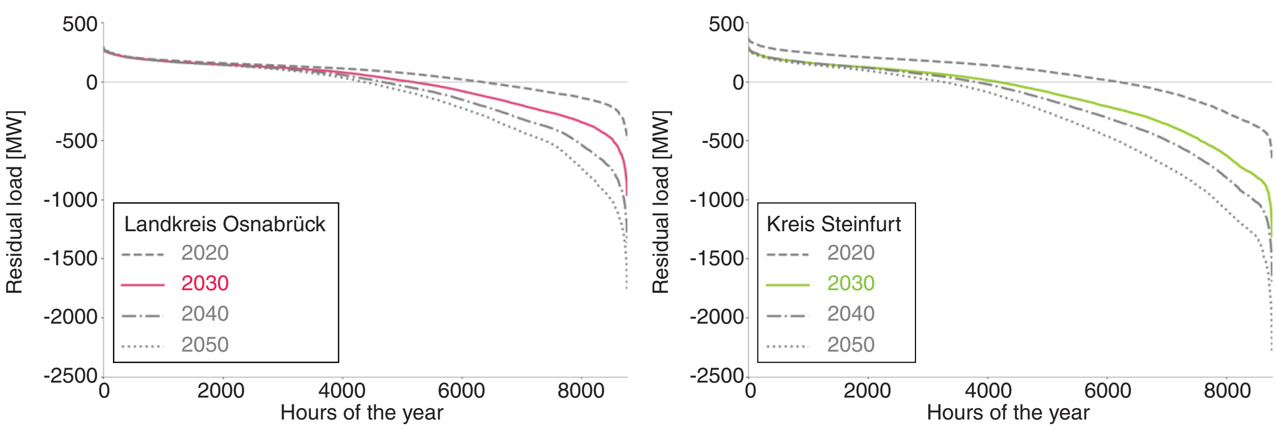

Figure 4: Annual load duration curve of the residual load (positive ordinate values: deficit, negative ordinate values: excess) in Landkreis Osnabrück (left) and Kreis Steinfurt (right), calculated with weather data (wind speed and solar irradiation) of 2005 [45,46], models for wind power and PV feed-in [44], a simplified biogas electric energy model, master plan targets for 2030 (see Table 1 to 3) and ENTSO-E load profile [47]

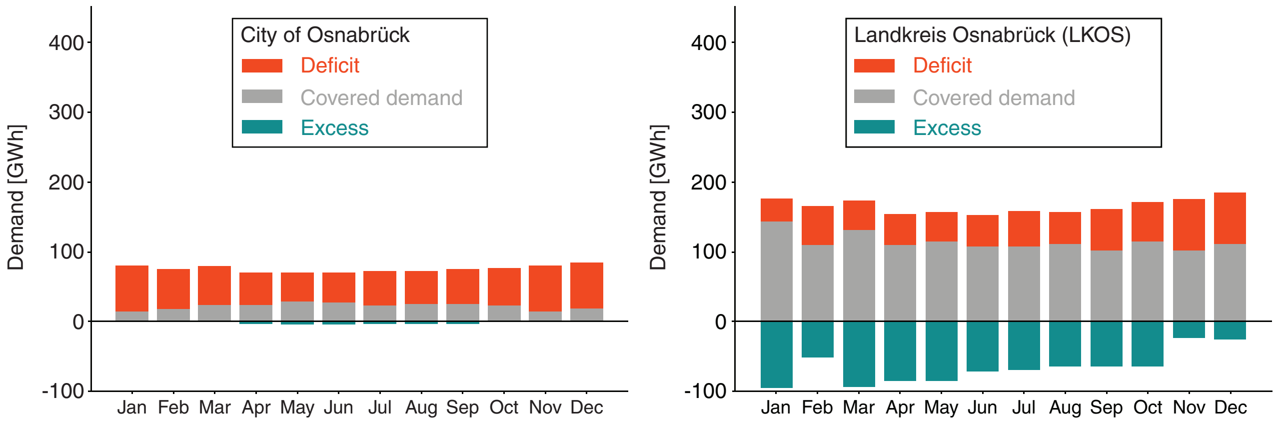

Figure 5: Monthly demand coverage, deficit and excess energy in the City of Osnabrück (left) and the Landkreis Osnabrück (right), calculated with weather data (wind speed and solar irradiation) of 2005 [45,46], models for wind power and PV feed-in [44], a simplified biogas electric energy model, master plan targets for 2030 (see Table 1 to 3) and ENTSO-E load profile [47]

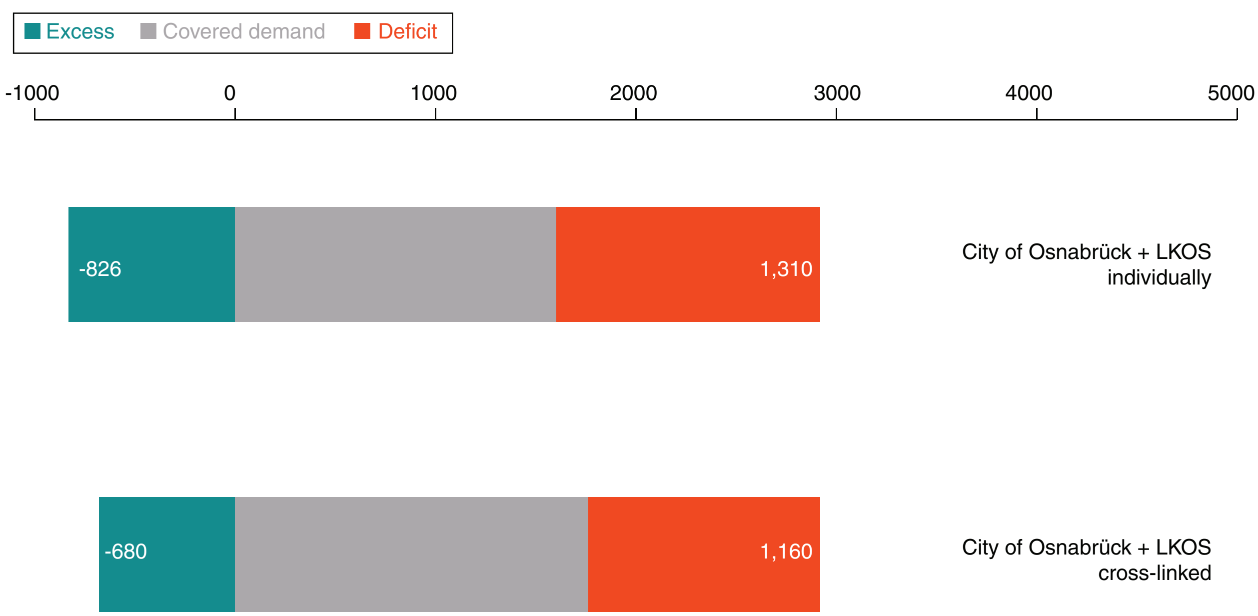

Figure 6: Annual demand coverage, deficit and excess energy of the Landkreis Osnabrück (LKOS) and the City of Osnabrück taken individually with added up values, compared to both regions cross-linked, calculated with weather data (wind speed and solar irradiation) of 2005 [45,46], models for wind power and PV feed-in [44], a simplified biogas electric energy model, master plan targets for 2030 (see Table 1 to 3) and ENTSO-E load profile [47]

year. In February, November and December the excess energy is slightly decreased. The increased excess e.g. in January is mainly due to good wind conditions. There is 188 GWh electric energy production from wind power in January at an installed wind power capacity of around 500 MW (see Table 1) which would correlate to more than 4,500 full load hours if projected to one year. Solar irradiation conditions were poor during the same period. Calculations result in only 25 GWh electric energy production in the Landkreis Osnabrück at an installed capacity of around 720 MW (see Table 1). This also explains why the City of Osnabrück exhibits zero overproduction in January as the renewable energy supply is mainly based on PV.

Figure 6 compares the sum of the individual values of annual excess, covered demand and deficit (variation 1)

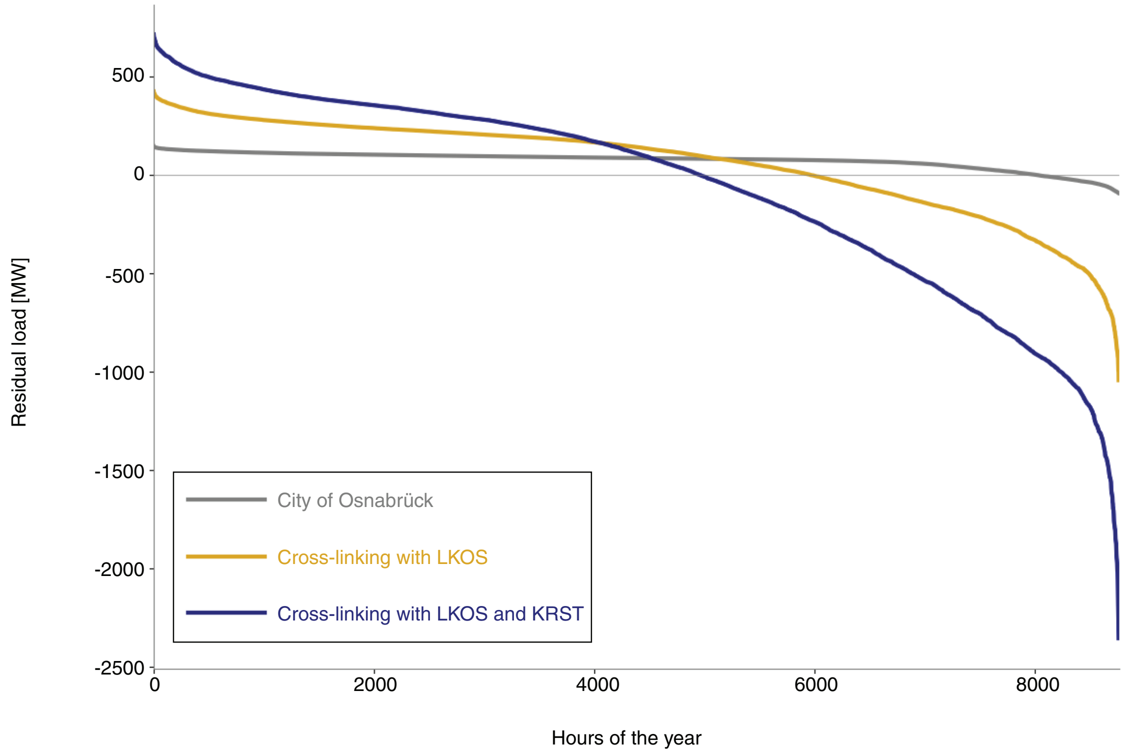

Figure 7: Annual load duration curve of residual load (positive ordinate values: deficit, negative ordinate values: excess) in the City of Osnabrück alone and either cross-linked with only the Landkreis Osnabrück (LKOS) or with the Landkreis Osnabrück and the Kreis Steinfurt (KRST), calculated with weather data (wind speed and solar irradiation) of 2005 [45,46], models for wind power and PV feed-in [44], a simplified biogas electric energy model, master plan targets for 2030 (see Table 1 to 3) and ENTSO-E load profile [47]

with the cumulative values when cross-linking both regions (variation 2). In contrast to variation 2, variation 1 does not use synergies in energy supply and demand, which means that overproduction in one region is not used to cover a deficit in the other region.

Cross-linkage of the City of Osnabrück with Landkreis Osnabrück results in a slight increase of coverage of cumulative demand and a slight decrease in cumulated energy deficit.While the cumulated annual deficit of the individual regions is around 45% of the annual demand (annual deficit of 670 GWh in the City of Osnabrück plus 640 GWh in the Landkreis Osnabrück, compared to an annual demand of 910 GWh in the City of Osnabrück plus 2,000 GWh in the Landkreis Osnabrück), it decreases to 40% for cross-linked regions (mutual annual deficit of 1,160 GWh compared to annual demand of 2,910 GWh), resulting in a self-sufficiency degree of 60%.

The excess energy is accordingly reduced (from 800 GWh in Landkreis Osnabrück plus 26 GWh in the City of Osnabrück to 680 GWh in the cross-linked variation). Proportionally, the share of overproduction in annual electric energy demand drops to 23%, compared to 40% in the Landkreis Osnabrück and 3% in the City of Osnabrück when examined as individual regions (see section 3.1).

For the City of Osnabrück, the cross-linkage with its rural neighbor is beneficial since it can more than double its self-sufficiency from 27% to 60% in connection with the Landkreis Osnabrück. The Landkreis Osnabrück, however, reduces its individual self-sufficiency of 68% by 8 percentage points. From the perspective of the rural region, there is thus no direct benefit of cross-linkage to the city, but could lead to an economic incentive by selling electricity to the city in future regional energy markets. The individual specific deficit energy converted into values per resident is 4.1 MWh/resident for the City of Osnabrück and 1.8 MWh/resident for the Landkreis Osnabrück. Cross-linking both regions, the deficit results to 2.2 MWh/resident (1,160 GWh to 520,000 residents), which is an increase from the perspective of the Landkreis Osnabrück and would lead to greater efforts in providing flexibility.

Figure 7 finally shows both cross-linking options (cross-linkage with the Landkreis Osnabrück and cross-linkage of the total region) compared to the City of

Osnabrück as an individual region. When enlarging the region and implementing Kreis Steinfurt, the mean specific deficit drops to 1.6 MWh/resident (1,530 GWh to 963,000 residents), which would be beneficial for both, the City of Osnabrück and the Landkreis Osnabrück. For Kreis Steinfurt, however, it is an increase as its individual specific deficit amounts to only 1.1 MWh/resident. The deficit of Kreis Steinfurt as an individual region increases when using synergies by cross-linking it to the rest of the region and analyzing electricity production and demand from the view of the total region. Thus self-sufficiency decreases from 79% to 70% (see also section 3.1).

3.3 Influence of different input weather data and load profiles

Simulation data generally rely on the quality of the input data. To validate the results presented in the prior sections, the influence of two significant input parameters was analyzed: weather data and load profile. Weather data (wind speed and solar irradiation) are directly linked to the generated electric energy of the fluctuating RES-E. Together with the shape of the load profile they directly influence the residual load.

Figure 8 shows the predicted self-sufficiency degrees of the three regions for 2030, calculated with weather data of 17 different years (1998 to 2014). Blue symbols represent the results of the weather year 2005 used for the calculations in the prior sections. The resulting self-sufficiency degree varies between 76 and 82% in Kreis Steinfurt (compared to 79% for 2005 data), between 65 and 72% in Landkreis Osnabrück (compared to 68% for 2005 data) and between 24 and 28% in the City of Osnabrück (compared to 27% for 2005 data). Due to low installed RES capacity in the City of Osnabrück, the effect of the weather data on the self-sufficiency degree is lower than in the rural regions. Regarding the cross-linked synergetic calculation of the total region comprising Kreis Steinfurt, Landkreis Osnabrück and the City of Osnabrück (not shown in the figure), self-sufficiency varies between 67 and 74% (compared to 70% for 2005 data) The relative error due to different weather data on the presented results can thus be estimated to be less than 10%.

Regarding the influence of different load profiles on the results, the ENTSO-E load profile [47], used for all previous analyses, was compared to BDEW standard load profile H0 [48]. Both load profiles represent extreme approaches: the ENTSO-E load profile delivers

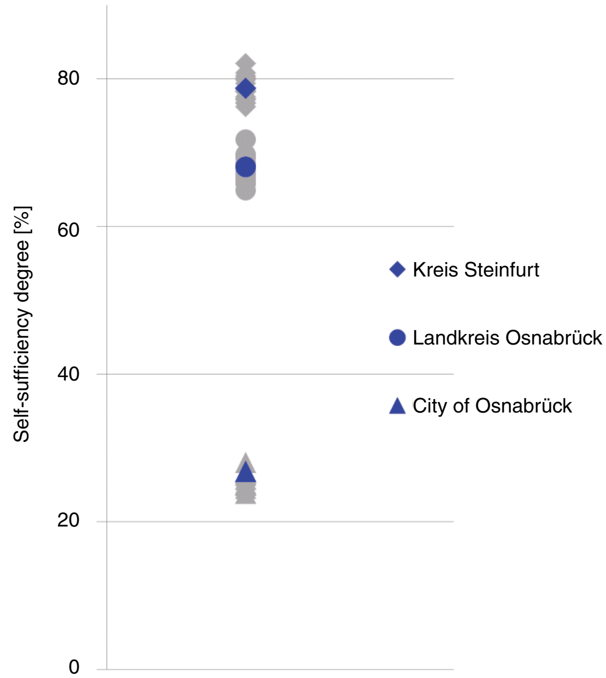

Figure 8: Self-sufficiency degree of Kreis Steinfurt, Landkreis Osnabrück and the City of Osnabrück, calculated with the weather data of the years 1998 to 2014 [45,46], models for wind power and PV feed-in [44], a simplified biogas electric energy model, master plan targets for 2030 (see Table 1 to 3) and ENTSO-E load profile [47]

curves between 141 and 327 MW and the BDEW standard load profile H0 curves between 77 and 411 MW for the assumed annual electric energy demand of the Landkreis Osnabrück in 2030 (see Figure 2 in section 2). The ENTSO-E load profile is thus too smooth and the BDEW standard load profile H0 too sharp for a region of this size.

Figure 9 depicts the influence of the two load profiles on the monthly demand distribution for the Landkreis Osnabrück in 2030. The profiles show significant deviations in seasonal distribution. When assuming the BDEW standard load profile H0, demand increases in summer and decreases in winter. The BDEW profile thus leads to a contrarian monthly distribution. A possible explanation can be found in the origin of the profiles. The ENTSO-E load profile represents the electric load at maximum voltage level. Therefore, the electric demand directly covered by RES-E feed-in in lower voltage levels is not included. As mainly PV power plants are connected to low voltage levels, the non-incorporated load of the ENTSO-E profile appears in summer.

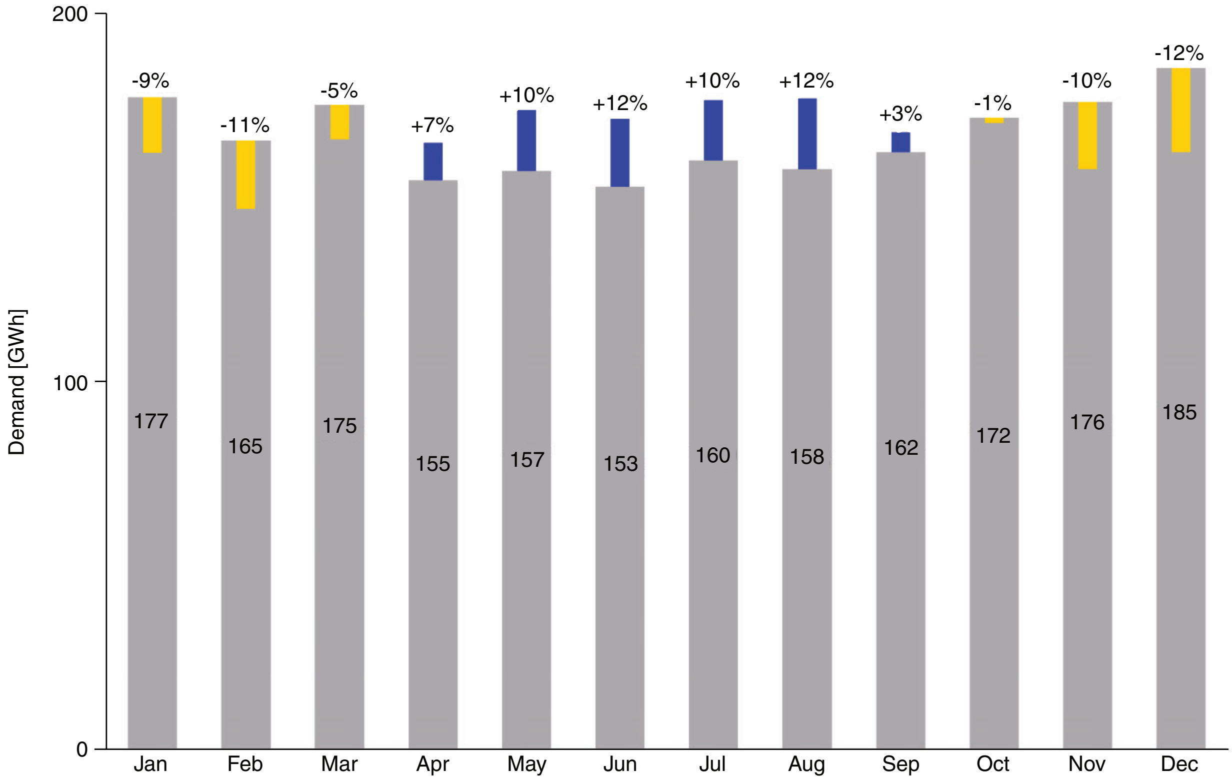

Figure 9: Monthly demand of the Landkreis Osnabrück, calculated with ENTSO-E load profile (data taken from [47]) and annual electric energy demand target of 2030 (see Table 3), and monthly percentage deviations of calculation with BDEW standard load profile H0 (data taken from [48])

Hence, the different profiles also lead to different distributions of deficit and excess energy among the months of one year, as depicted in Figure 10. The deficit energy is accordingly higher in the summer months with the BDEW standard load profile H0 compared to the ENTSO-E load profile, whereas the behavior of the excess energy is the exact opposite (higher in winter and lower in summer when assuming BDEW standard load profile compared to ENTSO-E load profile).

Considering one year in total, the use of the two different load profiles result in the following values on the example of Landkreis Osnabrück and the scenario year 2030): deficit decreases from 640 GWh (ENTSO-E profile, see section 3.1) to 620 GWh (BDEW H0 profile), excess energy from 800 GWh (ENTSO-E profile) to 780 GWh (BDEW H0 profile). Thus, the resulting annual deficit and excess energy values are nearly the same. Therefore also, there is almost no difference in the resulting self-sufficiency degree. The relative error on the presented results due to assuming different load profiles can thus be estimated at less than 4%. This also applies for the cross-linking options.

The use of different load profiles leads to only little changes in resulting self-sufficiency degrees, but affects the monthly distribution of deficit and excess energy and the resulting periods like summer or winter. This also applies for different weather years (although not considered in this study) and could have consequences for providing flexibility like power to heat or other flexibility options, as for example described by Niemi et al. [50] who connect different energy carrier networks to distributed renewable energy generation (for example convert surplus electricity into thermal energy) to improve energy sustainability in urban areas.

4. Discussion and Conclusion

In this study the potential of two rural municipalities for providing a neighboring city with electric energy was determined and the different potential of renewable

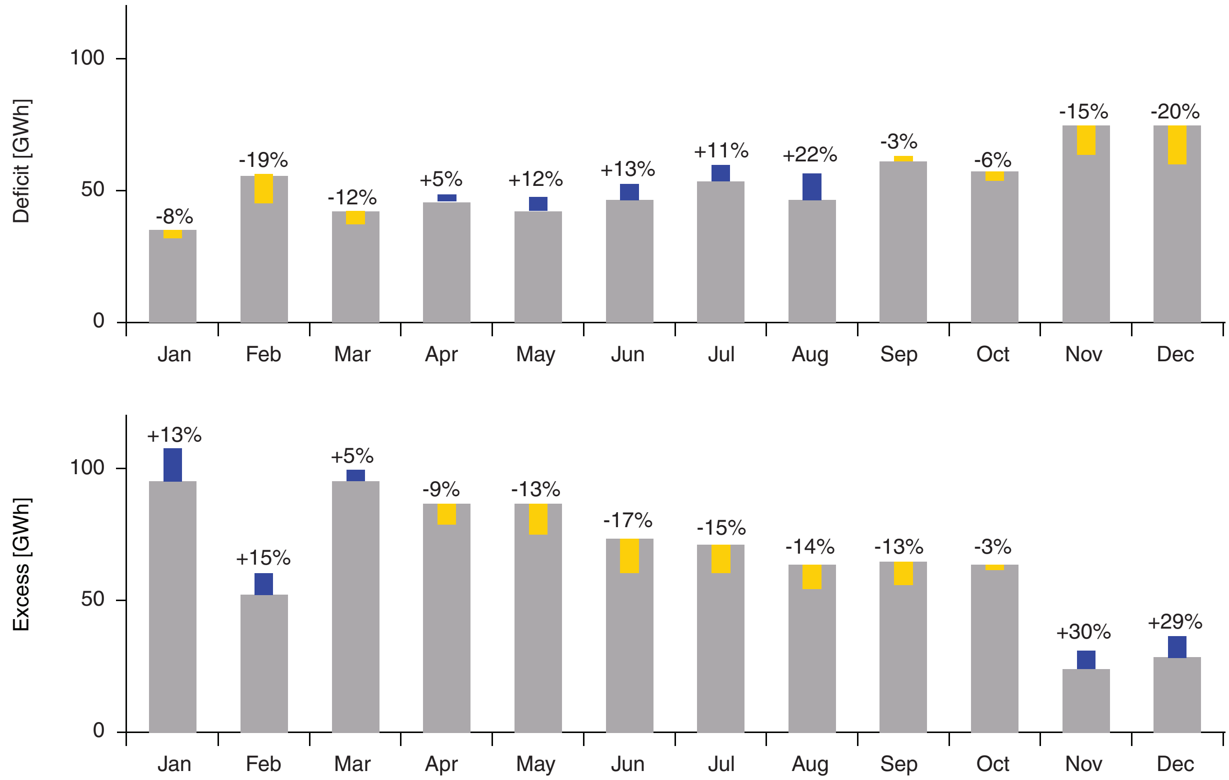

Figure 10: Monthly deficit (top) and excess (bottom) energy of the Landkreis Osnabrück, calculated with ENTSO-E load profile (data taken from [47]) as in Figure 5, and monthly percentage deviations of calculation with BDEW standard load profile H0 (data taken from [48]).

demand covering and self-sufficiency in urban and rural regions was evaluated. Three regions were studied in detail based on long-term projections and political decisions for the installation of renewables, the City of Osnabrück in the north-west of Germany and its neighboring rural municipalities, Landkreis Osnabrück and Kreis Steinfurt. All sub-regions of the total region under study are master plan regions funded by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) and aim at a fast increase of renewable energy sources and self-sufficiency on an annual balance. Deficit and overproduction in urban and rural areas were determined and the potential of cross-linking the rural regions to the city was analyzed. To calculate real self-sufficiency degrees the residual load was analyzed by transferring the expansion scenarios of the region's RES-E targets, mainly the increase of wind and photovoltaic power, to hourly time step based load and generation profiles.

The different potentials of installing RES-E due to structural differences in urban and rural areas lead to a great range of predicted real self-sufficiency degrees resulting from the time step based RES-E generation and electric demand, without implementation of storage. The city is not capable of meeting its electric energy demand only by the targeted increase of RES-E within its urban area. Most hours of the year show a deficit in energy supply. The rural regions, on the other hand, are characterized by far greater expansion targets of RES-E compared to the city. Depending on the master plan year, this leads to an overproduction in up to half of the hours of one year.

Using excess energy from the rural regions to provide the deficit in the urban area leads to a benefit for the total system. The City of Osnabrück benefits primarily since self-sufficiency, from the city's point of view, increases significantly cross-linked with the neighboring regions. To some extend also the Landkreis Osnabrück benefits, which becomes apparent when cross-linking the total region. The self-sufficiency of the total region increases compared to the examination of Landkreis Osnabrück as a single region. The Kreis Steinfurt, having the largest expansion targets of RES-E, takes on the role of the supplier.

Figures 11 and 12 summarize the results. The annual values of deficit and excess energy, and the resulting self-sufficiency degree for the priorly discussed variations are shown. Figure 11 shows deficit and excess energy for the single regions compared to both variations of cross-linking, exemplarily for the year 2030. Deficit energy is nearly the same in all regions, whereas excess differs considerably. Cross-linking the regions leads to lower deficit and excess energy compared to the respective summed up values due to the use of synergies in energy production and demand. Self-sufficiency and share of excess energy in annual electric energy demand, as shown in Figure 12, from the perspective of the City of Osnabrück significantly increases, but decreases from the perspective of the Landkreis Osnabrück when cross-linking both regions.

During the master plan process, stakeholders from the City of Osnabrück and the surrounding districts, Landkreis Osnabrück and Kreis Steinfurt, are discussing the question of how much the City of Osnabrück has to profit from its rural neighbors. The relations of the city and its surroundings are analyzed and possible solutions are discussed. The City of Osnabrück has great interest in getting support in electricity supply from their

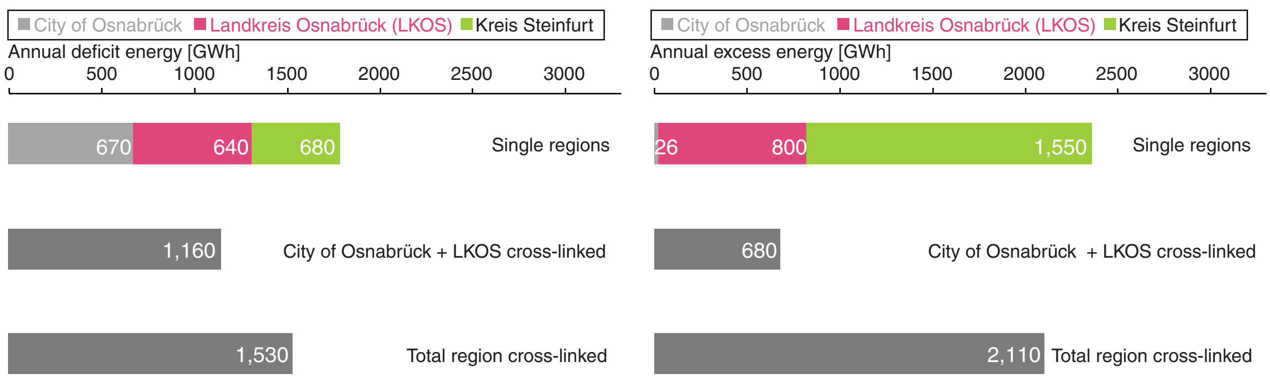

Figure 11: Deficit (left) and excess (right) energy for sub-regions and various cross-linking options, calculated with weather data (wind speed and solar irradiation) of 2005 [45,46], models for wind power and PV feed-in [44], a simplified biogas electric energy model, master plan targets for 2030 (see Table 1 to 3) and ENTSO-E load profile [47]

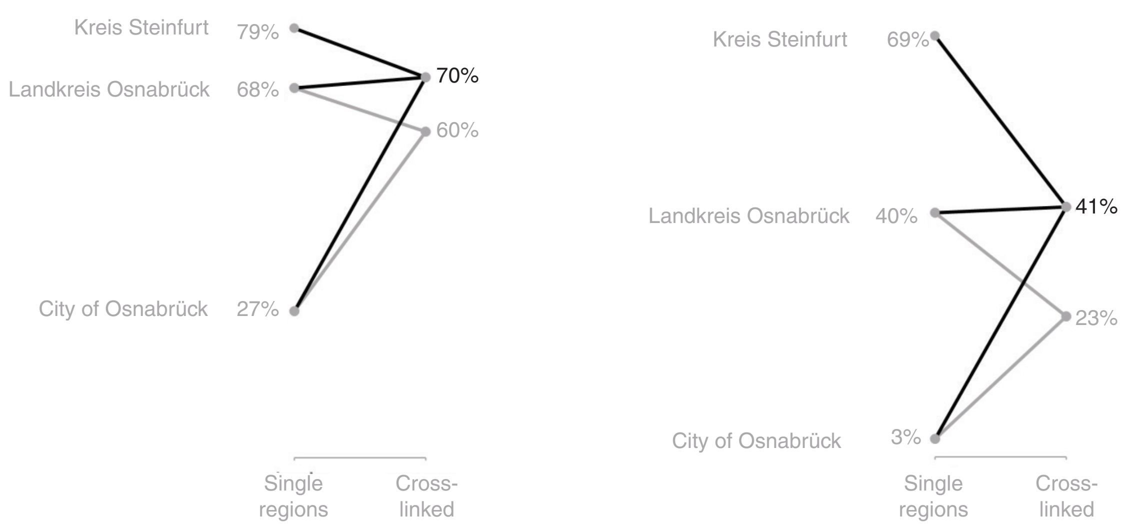

Figure 12: Change of self-sufficiency degree (left) and share of excess energy in annual electric energy demand (right), calculated with weather data (wind speed and solar irradiation) of 2005 [45,46], models for wind power and PV feed-in [44], a simplified biogas electric energy model, master plan targets for 2030 (see Table 1 to 3) and ENTSO-E load profile [47]

surrounding municipalities to achieve its own master plan targets. One main outcome from that discussion is that the city should increasingly focus on the reduction of energy demand, which is on the other hand not the most important case for rural areas (when only the system boundaries of the particular rural municipality are considered for achieving the master plan targets). However, a collaboration of cities and their surroundings will always be necessary, as it is not possible to fully cover the demand by renewables within an urban territory.

Cross-linking urban and rural regions is necessary and reasonable. For cities it is a significant component in the process of achieving sustainable energy supply. Seen from the perspective of rural regions, cross-linkage to a city decreases the possible self-sufficiency resulting from the rural renewable energy potential. However, cross-linkage should be the first choice for rural regions before considering further flexibility options like storages which is significant considering the discussion on e.g. energy storage demand. Further, urban-rural cooperations facilitate a regional compensation of load and generation, which has the potential to reduce generation peaks of RES-E and could therefore reduce supraregional grid expansion.

The potential of cross-linking, however, is also technically limited. As the regarded City of Osnabrück has no own fossil energy production, it already depends on the existing power grid. Thus, the focus of our study is system analysis based on energy flows, but we recommend evaluation of power network calculations within the context of urban-rural energy supply as part of further studies. Further studies must also ask the question how the supplying regions can profit. Possible benefit for rural regions could be a monetary equivalent for the supplied energy. An influence of different weather years and load profile assumptions on deficit and excess energy was found on a monthly basis and must be discussed when considering further flexibility options like power-to-heat.

The calculated deficit and overproduction peaks even after cross-linkage reveal a substantial regional potential for load levelling by flexibility options. Flexible biogas production can be used to further increase self-sufficiency degrees, which could be shown in a separate study [51]. Sector coupling and smart energy system concepts, like e.g. analyzed by [52-54], can use electrical overcapacities in the rural regions for the heat and transport sector and thus lead to a better holistic energy balance. Remaining overproduction and deficit has to be leveled either by the grid or electrical storages. As the region is located in the north of Germany, deficit compensation via the grid might be a good and economical option when using offshore wind energy. The total amount of available offshore wind energy is however limited due to Germany's small coastline.

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