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Energy Storage Potential in the Northern German Region Osnabrück-Steinfurt

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Abstract — The study shows the technical potential of electrical storage solutions for a so called energy region in the northern part of Germany. Based on the model region's targets for the increase of renewable energy capacity and by using annual simulations in hourly time steps, required storage capacity was calculated. Focus is on the electric energy supply. Results were determined under the requirement of various self-sufficiency degrees. Unlike the common calculation in the region's energy concepts, the self-sufficiency degree was determined solely by considering the directly consumed energy from fluctuating renewable energies or from storage. Thus, a bridge is built to the partly abstract ambitions of energy autarky. Further, various operation sites and appropriate storage technologies were analyzed.

Keywords—energy region; self-sufficiency; renewable energies; energy storage

I. MOTIVATION

The northern German model region Osnabrück-Steinfurt is one of Germany's *energy regions* [1,2] that aim to become independent of the import of fossil resources and plan to expand renewable energy supply significantly. Often, energy regions also strive to achieve energetic self-sufficiency by a decentralized renewable energy supply within the region [3]. The required renewable energy capacity in energy regions is usually calculated by an annual balance of energy supply and consumption. Those balances do not consider real supply and load profiles, though, and therefore do not include storage requirements.

In an interdisciplinary research project financed by the Ministry of Science and Culture of Lower Saxony, Germany, engineering, economy, marketing and law scientists investigate the possibility of real electrical self-sufficiency of the model region by implementation of electrical storage solutions. Research questions are:

- Theoretically required storage capacity for a total self-sufficiency
- Economically and technically reasonable storage capacity and resulting degree of self-sufficiency
- Possible technical storage solutions for the model region
- Influence of localization of storages (central, semi-central, decentralized) within the model region
- Business models and the legal framework
- Motivation to install and invest in storages
- Influence of storages on consumer acceptance and on the region's attractiveness

This paper focusses on the technical questions regarding storage demand and solutions for different storage operation sites within the model region.

II. MODEL REGION OSNABRÜCK - STEINFURT

The model region Osnabrück-Steinfurt is a master plan region with targets regarding the reduction of greenhouse gas emissions by 95 % and energy demand by 50 % until 2050 compared to 1990. Its master plan goals are basis for the present study. The region consists of four adjoining sub regions, two rural regions (Kreis Steinfurt and Landkreis Osnabrück) and two cities (Osnabrück with 160,000 inhabitants and Rheine with 73,000 inhabitants), see figure 1. Total electricity demand of the region currently amounts to approx. 6,000 GWh/a [4] and differs considerably between the rural regions and the two cities. Table 1 shows the planned development of renewable energy supply of the region in total for the years 2020 to 2050 and the annual self-sufficiency degree which would be achieved. The master plan targets for the year 2030 have been displayed separately for both rural areas and the City of Osnabrück in Table 2. The annual self-sufficiency for the total model region in the year 2030 results to around 100 %.

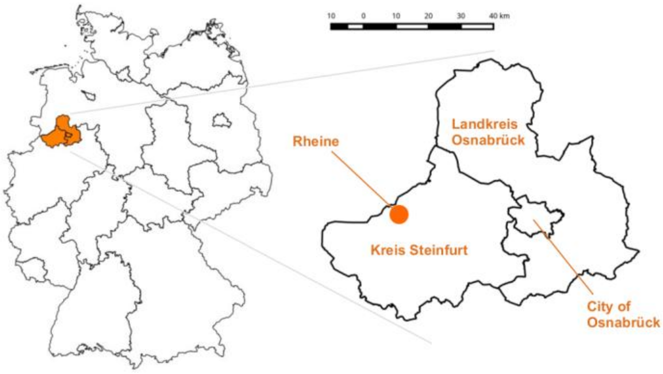

Fig. 1: Location of the model region in Germany.

TABLE I. PLANNED DEVELOPMENT OF RENEWABLE ENERGY SUPPLY IN THE MODEL REGION FOR THE YEARS 2020 TO 2050, ASSUMPTIONS BASED ON [4,5]

	2020	2030	2040	2050
Installed wind energy capacity in MW	1,005	1,516	1,830	2,190
Installed photovoltaic capacity in MW	834	1,491	2,084	2,869
Annual chemical biogas potential in GWh/a	1,497	2,267	1,942	1,933
Annual electric energy demand in GWh/a	5,454	5,165	5,140	5,104
Resulting self-sufficiency degree (annual balance)[1]	61 %	101 %	122 %	151 %

TABLE II. PLANNED DEVELOPMENT OF RENEWABLE ENERGY SUPPLY FOR 2030 AND THE RESULTING SELF-SUFFICIENCY DEGREES FOR THE SUB REGIONS[2], ASSUMPTIONS BASED ON [4,5].

	Kreis Steinfurt	Landkreis Osnabrück	City of Osnabrück
Installed wind energy capacity in MW	1,000	499	17
Installed photovoltaic capacity in MW	582	721	188
Annual chemical biogas potential in GWh/a	1,459	755	53
Annual electric energy demand in GWh/a	2,255	1,997	913
Resulting self-sufficiency degree (annual balance)[3]	137 %	97 %	24 %

III. METHODS

The present study presents required storage capacities when examining the region's electric energy supply not only by annual values but rather using a time step based simulation of one year. The time increment τ was set to 1 h. Within the project, different modelling and simulation tools have been applied, among others the linear invest and dispatch model of the open energy modelling framework *oemof* [6] and Matlab/Simulink models.

Figure 2 shows the basic model components and the different storage operation sites (households, industry, and community) that were analyzed within the project frame.

Model input for a regional investigation (with centralized energy storage) are wind speed and solar irradiation of the year 2005 [7,8], the German load profile [9], planned installed capacities (wind power, PV), energy potentials (biogas) and electric energy demand as depicted in tables 1 and 2. Wind and PV feed-in were modelled using the power curve of an Enercon E82 with hub height of 100 m and an optimally-positioned crystalline silicon-based PV system. Model outputs are the storage dispatch and invests (required storage capacity).

[1] Based on the translation of installed capacity (wind energy and PV) in annual amounts of electric energy using typical full load hours of 2,000 (wind) and 900 (PV), and the translation of the chemical biogas potential in annual electric energy using an electrical efficiency of 0.38.

[2] Though Rheine has its own master plan, it is part of the region Kreis Steinfurt and therefore not specified here.

[3] See footnote 1.

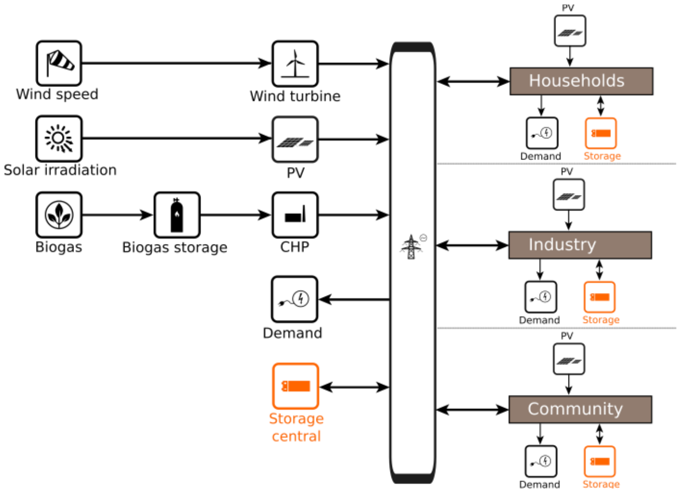

Fig. 2: Energy system model components with storage solutions at different operation sites. CHP: combined heat and power plant. Source icons: Reiner Lemoine Institut gGmbH.

In addition to covering the demand by renewable energy generation and energy storage components within the energy system it is possible to import energy from outside of the region when examining the region's energy supply with centralized storages, or from the grid when looking at e.g. households.

The minimum requirement of storage capacity to meet the electric energy demand of one year under the assumption of different self-sufficiency degrees (which restrict the imported energy) was calculated by the following procedure. The self-sufficiency degree s is the ratio of the annual sum of electric energy which has been directly used for demand coverage in each hour of the year and the annual demand E_{annual}. To meet the hourly demand, electric energy can be drawn directly from renewable energy sources or from the energy storage. The relation between E_{annual}, s and the import power P_{import}, which meets the residual demand, is as follows:

$$\sum_{t=1}^{8760} P_{import}(t) * \tau = (1 - s) * E_{annual} \qquad (1)$$

Storage demand and the comparison of different storage solutions were determined from a future power supply system's point of view with high shares of fluctuating renewable energy sources. The focus of this analysis is on the reliability of supply in terms of balancing electricity generation and consumption. Other criteria of security of supply like grid stability have not been investigated in this study.

Further, this analysis is not targeted on presenting how a region can become 100 % self-sufficient. Rather, the influence of the partly ambitious renewable energy's expansion targets on storage capacities is demonstrated.

IV. RESULTS

A. Technical storage solutions within the model region

Several electric energy storage principles were examined in terms of feasibility in the model region: centralized storage

solutions include pumped hydropower in former coal mines, high pressure air cavern storage, power to gas (PtG), and electrochemical battery storages. Decentralized storage possibilities include community battery storage [10,11], industry battery storage, as well as household batteries in combination with photovoltaic plants and fast-charging batteries for e-mobility fleets.
Due to the geological conditions, the potential for high power centralized storage is very low. The only coalmine in the considered area could not be taken into account for different reasons. Another possibility for centralized storage capacity would be high pressure air cavern storage in the northwestern part of the region. Caverns for natural gas storage are present in the region. Thus, from a geological point of view cavern storage is possible. However, in order to get rid of the sole the erection of caverns needs transport options like a connection to the North Sea.
Battery storages and PtG remain realistic future storage solutions within the model region. It is assumed that connections to the gas distribution system with sufficiently high flow rates as well as CO_2 sources for hydrogen methanation are available in sufficient quantity.

B. Storage demand of the model region using different storage technologies

The storage demand of the model region (see left side of the energy system model in figure 2) was determined using different storage technologies. Key restrictions were real self-sufficiency degrees as defined in equation 1.
Figures 3 and 4 compare achievable self-sufficiency degrees for battery (lithium-ion, sodium–sulfur) and PtG with re-conversion to electric energy for various simulation years. Assumed technical storage parameters are depicted in table 3.

TABLE III. TECHNICAL STORAGE PARAMETERS

	Lithium-ion	Sodium-sulfur	PtG
Cycle efficiency	0.95	0.75	0.35
C-rate	1	1/6	1
Usable range	10 to 90 %	10 to 90 %	100 %

The sodium-sulfur technology has a higher storage capacity requirement compared to lithium-ion in all cases due to its lower efficiency and C-rate. In 2020, an energy system using sodium-sulfur storages reaches a self-sufficiency maximum of 75 %. Using lithium-ion batteries, the maximum self-sufficiency can be increased to 80 %. However, the required storage capacity would be unrealistically high and was thus not depicted in figure 3.
Using the generation input of all other master plan years (2030 to 2050) 100 % self-sufficiency can theoretically be achieved. A self-sufficiency of 95 % in the simulation year 2030 requires 24 GWh using sodium-sulfur or 17 GWh using lithium-ion batteries. More realistic are storage capacities below 10 GWh. Thereby 85 to 90 % self-sufficiency is a realistic goal for the year 2030.
With increasing renewable energy input the required storage capacity decreases. It is also striking that for a self-sufficiency degree of 80 % (from 2030 on) no storage capacity is required, 2050 even 85 % self-sufficiency are achieved without storages.

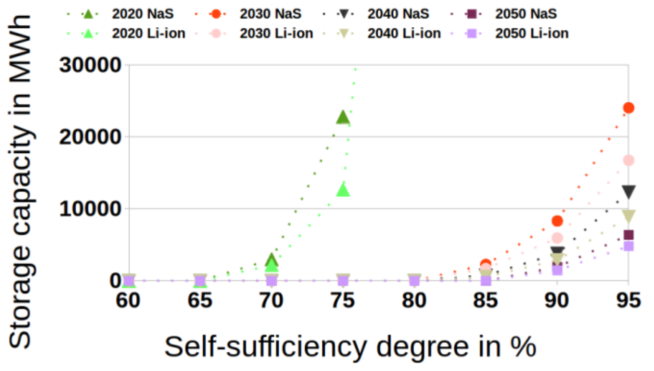

Fig. 3: Sodium-sulfur (NaS) and lithium-ion (Li-ion) battery storage capacity for various self-sufficiency degrees of the model region, simulated with input data of the years 2020 to 2050 (see table 1). Biogas was considered with continuous electric output.

Using PtG, depicted in figure 4, tends to result in higher storage capacity requirements. Due to the need for more excess energy compared to battery storages, in 2020 a self-sufficiency of maximum 70 % can be reached with a storage capacity of 5.5 GWh. A theoretical 100 % self-sufficiency cannot be reached before 2040, unlike using the technologies NaS or Li-ion.
For all simulations only one weather year was applied to calculate the wind and PV feed-in. Years with strongly deviating weather conditions could lead to other results than those presented.

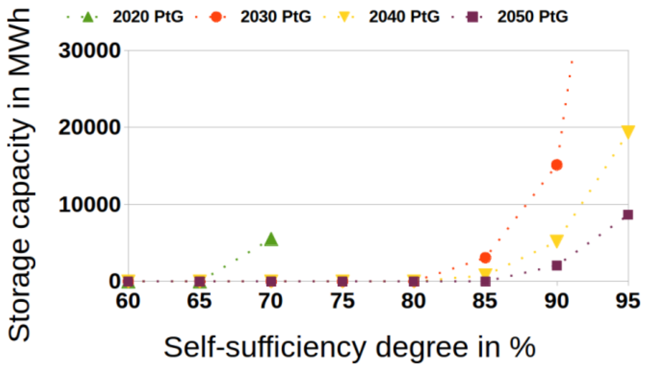

Fig. 4: PtG storage capacity for various self-sufficiency degrees of the model region, simulated with input data of the years 2020 to 2050 (see table 1). Biogas was considered with continuous electric output.

PtG is the only (today foreseeable) storage solution that provides sufficient capacity to bridge several days or even weeks of electricity demand. At the same time, it needs a considerable energy excess due to its poor efficiency. Within the model region, the necessary energy excess will be available

between 2040 and 2050. Battery storages, on the other hand, are good solutions for balancing diurnal fluctuations.
From today's point of view, a combination of PtG storage to bridge long term energy deficits and electrochemical storages for short term balancing can be a good solution within the model region for the years 2030 and following.

C. Differences in storage demand within the sub regions

The rural regions Kreis Steinfurt and Landkreis Osnabrück were analyzed regarding their difference in storage demand as a sub-region. Figure 5 shows the required storage capacity for both rural regions and for self-sufficiency degrees between 80 and 90 %, exemplary for the year 2030. Further, the biogas potential has been considered in two variations. Variation 1 uses a continuous electric output throughout the year whereas in variation 2, flexible biogas potential was simulated by doubling the output capacity
Results for the rural areas show that planned renewable energy capacity for 2030 (annual self-sufficiency degree of 100 %) leads to real self-sufficiency rates of approx. 80 % for Landkreis Osnabrück and 86 % for Kreis Steinfurt when considering fluctuating supply and consumption load profiles. The required storage capacity for 100 % real self-sufficiency degree is immense (18 GWh for Kreis Steinfurt and even 39 GWh for Landkreis Osnabrück; not depicted in the diagram) and thus neither economically nor technically feasible. With increasing tolerated energy import the storage capacity requirements decrease significantly. For a 90 % self-sufficiency degree storage capacities of 0.6 GWh for Kreis Steinfurt and 2.3 GWh for Landkreis Osnabrück are required.
A flexible use of the biogas potential leads to a further reduction in storage capacity. For 90 % self-sufficiency the storage capacity is reduced to almost zero (Kreis Steinfurt) and 1.9 GWh (Landkreis Osnabrück). Moreover, the self-sufficiency degree without the use of storages is increased to 82 % in Landkreis Osnabrück and even 89 % in Kreis Steinfurt.

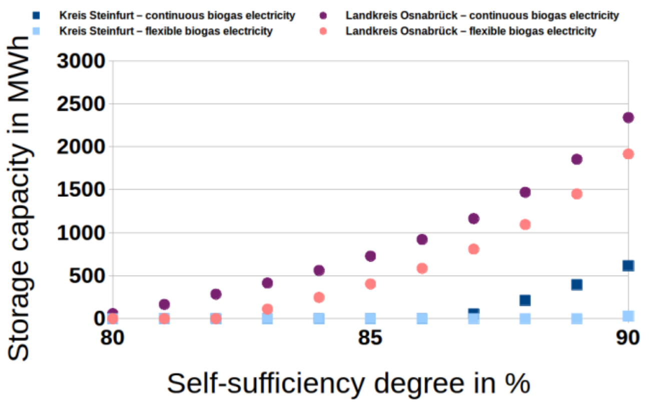

Fig. 5: Calculation of required storage capacity for different real self-sufficiency degrees assuming the planned development of renewable energy supply for 2030 as depicted in table 2 - influence of constant or flexible biogas plant operation. Storage parameters were set to: 0.8 (cycle efficiency), 1/6 (C-rate), and 100 % (usable range).

The cumulative storage capacity for 90 % real autarky of the two regions is approx. 3 GWh. This value can be reduced to approx. 2.2 GWh by the linkage of the two load-profiles prior to the use of energy storage (see figure 6). The City of Osnabrück cannot independently self-supply itself due to low renewable energy potentials, but can serve as a drain for the excess in the rural regions when interconnecting the sub-regions. Figure 6 also shows the total required storage capacity for an interconnected system of the City of Osnabrück and the two rural regions.

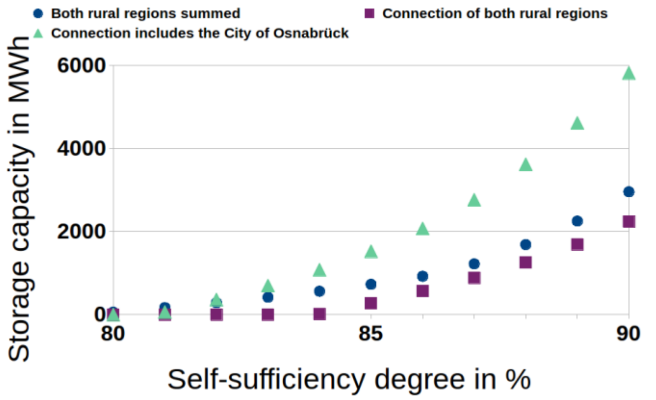

Fig. 6: Calculation of required storage capacity for different real self-sufficiency degrees assuming the planned development of renewable energy supply for 2030 as depicted in table 2. Storage parameters were set to: 0.8 (cycle efficiency), 1/6 (C-rate), 100 % (usable range). Biogas was considered with continuous electric output (variation 1).

D. Influence of storage location within the model region

The use of battery storages in combination with PV plants in private households is currently promoted in Germany. Decentralized electrical energy storage makes sense if the power consumption at the point of common coupling has a high rate and the fluctuation of power has a high level. A high demand of reactive power, harmonic currents and flicker can be a second reason to implement a decentralized storage system to improve the power quality. Usually, these requirements are often found in industrial sites, industrial areas and farms. Another future application will be fast charging stations for electrical vehicles especially if they are part of a fleet, light weight delivery vans or public transport stations (e.g. electrical / hybrid bus).
From 2012 on, the development of small size electrical storage systems in Germany was pushed by several start-up companies as well as big players like car manufactures and classical electricity producers. A market analysis identifies more than 60 companies that offer electrical storage systems for households in 2016. Starting with simple electrical energy storage systems, the systems are getting more and more integrated with heating, e-car charging, photovoltaic systems and emergency backup functions.
In order to judge the feasibility and costs of household electrical storage systems, a Matlab/Simulink model [12] of a household electrical energy system consisting of a photovoltaic

generator, a stationary energy storage, an e-car bidirectional charging station, an energy management system and the load behavior of standard households was developed. Input variables are weather data, geographical position, orientation of the photovoltaic-system, system efficiency, usage of car, and electricity consumption. The output data, depending on photovoltaic peak power and storage capacity, are self-consumption rate, self-sufficiency degree, and power demand from the public grid.

Due to the non-linear correlation, an investment for 100% independence is not feasible. In principle, both design goals, self-consumption rate and self-sufficiency degree, are diametric goals. Therefore designing a photovoltaic-storage-system is always a trade-off and is strongly dependent on consumer needs.

For calculation of pay back periods, a forecast of photovoltaic system cost and battery storage cost is necessary. Basic cost assumptions were set to:

- public electricity supply price: 0.291 €/kWh
- public electricity delivery price: 0.12 €/kWh (2016), 0.10 €/kWh (2030)

Further, the replacement costs of the battery system were considered after completing 5,000 cycles.

Today, the payback period is high and heavily depends on the storage capacity (see figure 7). However, in 2030, a payback period of six years will offer a self-sufficiency degree of around 50 % and a self-consumption rate of 75 %. With a payback period of eight years, nearly the whole simulation range can be used to establish a photovoltaic-storage system in 2030 (figure 8). The design of the system is not dependent on financial issues anymore and the point of operation can be chosen purely by customer needs.

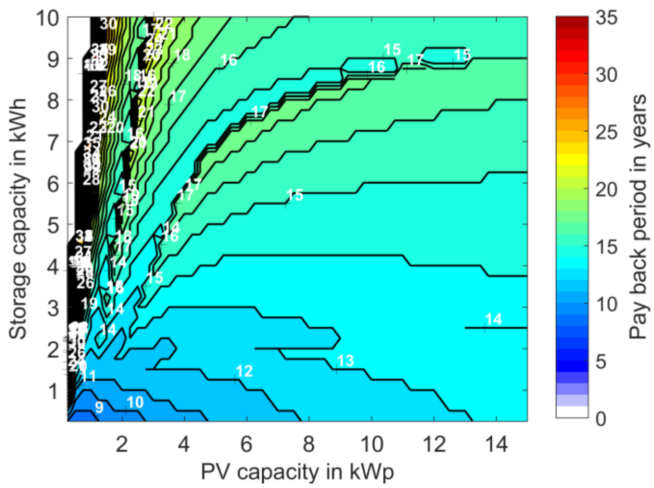

Fig. 7: Payback period when installing a photovoltaic/battery system in 2016 (cost assumptions based on [13,14]: PV system cost: 1,100 EUR/kWp, Battery storage cost: 658 EUR/kWh).

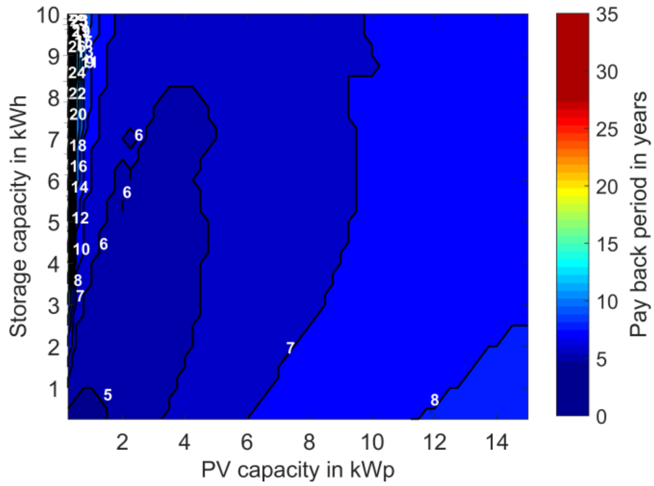

Fig. 8: Payback period when installing a photovoltaic/battery system in 2030 (cost assumptions based on [13,14]: PV system cost: 600 EUR/kWp, Battery storage cost: 133 EUR/kWh).

E-mobility can be differently integrated into the system, depending on the car usage. Assuming a family with two cars while the first car is used to commute to work and the second car is used for family matters throughout the day, the first car has a minor effect on the household energy system. Charging the first car at work would make sense. Probably part of the energy can be used in the evening and therefore the stationary energy storage can be designed smaller or the self-sufficiency degree will rise. The second car would be charged at home and would affect the self-consumption rate. Also, the stationary energy storage could be smaller because the car's storage capacity would be directly added as long as it is online with the private charging station.

Electric energy storage is rarely in use in industry and institutions up to now. Storages are mainly used for uninterruptable power supply, as vehicle batteries for forklifts, and for some other singular special applications. For economic reasons, electrical energy storage is normally not in use on a greater scale in the power supply of a whole industry unit.

Nevertheless, the following conditions can increase the economy of electric storage units in companies and institutions: reduction of the electricity price, which every producing company has to pay monthly according to their maximum power consumption (peak shaving), or increase in self-consumption rate in combination with solar or CHP electricity [15].

Results show that battery storages in (industrial) companies are profitable when using peak shaving as a business case. Although profitability is less than 1.5 % of the total electricity costs, battery storages in companies are ideal for using them with a second business case due to low resulting annual complete cycles. The self-consumption rate of existing photovoltaic plants increases only slightly when using a battery storage due to low solar electricity yield compared to high electricity demands of industrial companies.

In general, load fluctuations decrease by connecting more participants to a grid. Thus, the more decentralized the storage units are located within the supply chain, the higher the total amount of necessary storage capacity. With regard to sufficiency orientated business models which are described as one important key for transforming the energy system in [16], individual residential electricity storage (RES) systems were compared to community electricity storage (CES) [17].

Figure 9 shows the difference between the cumulated RES capacity of 10 different households (household profiles from [18,19]) in two variations. In variation 1, both, storage and PV capacity, were optimized. In variation 2, PV capacity was set to 10 kWp for each household or 100 kWp for the community.

Results show that CES capacity is always below the sum of individually required RES capacities. Optimization of PV and battery sizes (variation 1) leads to reasonable dimensions of battery storage in cases of high self-sufficiency degrees and balanced dimensions of PV and storage size (PV size is not depicted). However, this also means that the PV capacity at high self-sufficiency degrees is significantly higher than the preset 10 kWp for each household in variation 2. For 90 % self-sufficiency, for example, community PV capacity amounts to 115 kWp with a CES of 98 kWh in variation 1 (optimization case). Variation 2 with a fixed PV capacity of 100 kWp requires a CES of 292 kWh.

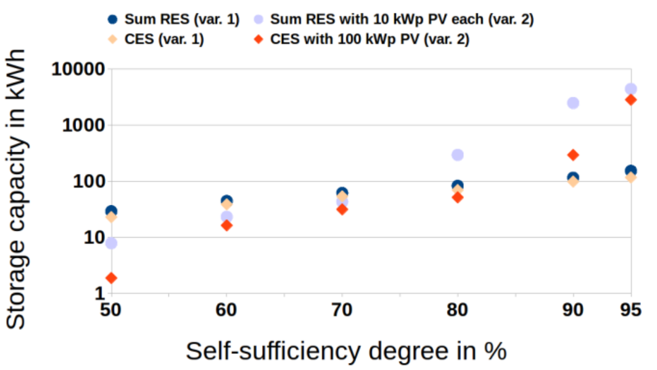

Fig. 9: Comparison of storage capacity of residential storages (Sum RES) and interconnected community electricty storage (CES) for 10 households with different load profiles. Variation 1: optimization of PV and storage capacity, variation 2: PV capacity preset to 10 kWp (RES) or 100 kWp (CES).

V. CONCLUSIONS

Planned renewable energy capacity in the model region amounts to real self-sufficiency of approx. 80 % in the year 2030 when considering fluctuating supply and consumption load profiles. The implementation of electrical storages can increase the self-sufficiency to 90 %. 100 % self-sufficiency is not feasible due to immense required storage capacities. Cross-linkage of regions or flexible use of biogas decreases storage demand. Technically reasonable storage solutions for the year 2030 and following years include PtG, central, community, and industry battery storages as well as household batteries in combination with photovoltaic plants. Generally, load levelling between several households or different regions decreases necessary storage capacity. Nevertheless, the feasibility of smaller storage solutions seems to be higher than that of large central solutions. The research team currently investigates the perception of and the motivation to invest in storages [16]. Community storages might be a good future option, when legal restrictions can be overcome.

ACKNOWLEDGMENT

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REFERENCES

[1] CIPRA: Energieautarke Regionen - Ein Hintergrundbericht der CIPRA. In: compact. 2010.
[2] Abegg, B.: Energy Self-sufficient Regions in the European Alps. In: Mountain Research and Development. 2011, 31, 367-371
[3] Späth, P.: Understanding the Social Dynamics of Energy Regions - The Importance of Discourse Analysis. In: Sustainability. 2012, 4, 1256-1273
[4] Stadt Osnabrück: Masterplan 100 % Klimaschutz Osnabrück, Osnabrück, Juni 2014.
[5] Amt für Klimaschutz und Nachhaltigkeit: Vom Projekt zum Prinzip – Masterplan für 100 % Klimaschutz für den Zukunftskreis Steinfurt, Köln, November 2013, im Auftrag des Kreises Steinfurt.
[6] Open energy modelling framework (oemof) – A modular open source framework to model energy supply systems. Licensed under GNU GPL 3. Available at https://github.com/oemof [16.04.2016].
[7] Stackhouse PW, Whitlock CH, editors: Surface meteorology and solar energy (SSE) release 6.0. Langley: Earth Science Enterprise Program, National Aeronautic and Space Administration (NASA); 2008. NASA SSE 6.0, http://eosweb.larc.nasa.gov/sse/ [16.04.2016].
[8] Gerlach, A., Stetter, D., Schmid, J., und Breyer, C.: PV and Wind Power – Complementary Technologies. In Proc. 26th European Photovoltaic Solar Energy Conference, Hamburg, 2011.
[9] ENTSO-E. Hourly load values of a specific country for a specific month, 2013. https://www.entsoe.eu/data/data-portal/consumption/ [16.04.2016].
[10] David Parra, Mark Gillott, Stuart A. Norman, Gavin S. Walker: Optimum community energy storage system for PV energy time-shift. In: Applied Energy, 2015, 137, 576-587
[11] Elisa Gaudchau, Matthias Resch, Alexander Zeh: Quartierspeicher: Definition, rechtlicher Rahmen und Perspektiven. In: Ökologisches Wirtschaften. 2016, 31, 26-27
[12] A. Sacchi, H.-J. Pfisterer: Simulation of a local smart grid system consisting of a stationary and a mobile energy storage, Batterietagung, Münster, 2016
[13] R. Kempener, E. Borden: Battery storage for renewables: Market status and technology outlook, IRENA , 2015.
[14] A. Schröder, F. Kunz, J. Meiss, R. Mendelevitch, C. von Hirschhausen: Current and Prospective Costs of Electricity Generation until 2050, DIW, 2013
[15] M. Voss, M. Kuhr, K. Kuhnke: Simulation of Electric Energy Storage in Hospitals and Institutions, 9th International Renewable Energy Storage Conference (IRES), Düsseldorf, 2015.
[16] Griese, K.-M., Wawer, T., Böcher, R. (2016): Suffizienzorientierte Geschäftsmodelle am Beispiel von Stromspeichern. Zukunftsfähige Ansätze in der Energiewirtschaft. In: Zeitschrift für Energiewirtschaft, Vol. 41 (2), S. 1-15
[17] C. Möller, M. Faulstich, S. Rosenberger: Storage demand in interconnected central and residential electricity systems, 10th International Renewable Energy Storage Conference (IRES), Düsseldorf, 2016.
[18] P. Hoffman, G. Frey, M. Friedrich, S. Kerber-Clasen, J. Marschall, M. Geiger: Praxistest „Moderne Energiesparsysteme im Haushalt“, IZES, Saarbrücken, 2012.
[19] T. Tjaden, J. Bergner, J. Weniger, V. Quaschning: Repräsentative elektrische Lastprofile für Wohngebäude in Deutschland auf 1-sekündiger Datenbasis, HTW, Berlin 2015, http://www.researchgate.net/publication/283615341 [15.04.2016].