# Storage requirments in urban energy systems for the integration of rooftop photovoltaics

Marlon Schlemminger*[1,2], Dennis Bredemeier[1,2], Alexander Mahner[1],

Raphael Niepelt[2,1], Michael H. Breitner[3], Rolf Brendel[1,2]

*[1] Department Solar Energy, Institute for Solid State Physics, Leibniz University Hanover*
*[2] Institute for Solar Energy Research Hamelin (ISFH)*
*[3] Information Systems and Management Institute, Leibniz University Hanover*
**Corresponding author. Email: schlemminger@solar.uni-hannover.de*

**ABSTRACT**

Solar photovoltaics (PV) on building rooftops is a major contributor to the decarbonization of energy systems and provides electricity close to consumption. However, high shares of PV challenge distribution grids and require energy storages due to the fluctuating daily and seasonal production profile. We calculate storage requirements for integrating electricity from rooftop PV into urban energy systems using a case study of the Hanover Region in Germany. The storage requirements change with the level of PV deployment. Aggregating production and consumption of the Hanover Regions we find that storage is not required until 44 % of the maximum realizable PV capacity potential is deployed. This is because hourly PV production never exceeds the hourly load. At 100 % of the realizable PV capacity, the region achieves a solar coverage of 37 % and supplies an additional 19 % of its annual consumption from PV using appropriate urban storages. This holds without considering any wind energy. A high-resolution spatial analysis shows that areas with high population density have significant balancing needs, as they exhibit high residual load and residual production, while being net consumers in the annual balance. In contrast, rural regions become net producers. Our results can support the planning of efficient energy storage systems and backup power plant capacities.

***Keywords:*** *Rooftop photovoltaics, storage requirements, urban energy systems, residual load.*

## 1. INTRODUCTION

The accelerating global shift towards sustainable energy sources has underscored the pivotal role of rooftop photovoltaics (PV) in urban energy systems. Harnessing solar power at the building level not only reduces reliance on conventional energy grids but also empowers urban areas to make substantial strides towards environmental sustainability. In addition, rooftop PV utilizes already sealed surfaces and thus eases the competition for land for renewable energies. This is particularly relevant in densely populated industrialized countries such as Germany [1]. To this date, rooftop PV makes up for over 40 % of the installed PV capacity globally and for 60 % of the installed PV capacity in Europe [2]. One contributing factor to this is the divergent perception of PV costs between homeowners and utilities. Utilities typically assess PV cost comparing them to the wholesale electricity market. In contrast, homeowners evaluate the costs of rooftop PV in relation to retail electricity prices. Retail prices are generally higher than market prices due to taxes and transmission and distribution costs. As cities increasingly embrace rooftop PV installations, the integration of these decentralized energy sources presents a multifaceted challenge, with storage emerging as a critical component in ensuring reliability and efficiency.

We delve into the pressing issue of storage requirements within urban energy systems, focusing on the seamless integration of rooftop photovoltaics. The intermittent nature of solar energy production necessitates effective storage solutions to bridge the gap between generation and demand, enabling a consistent and reliable energy supply for urban communities. We identify breakpoints for storage requirements of both short- and long-term using the concept of residual load and the general idea that storages enable a temporal shift of electricity from


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times with high PV electricity production to times with high residual load.

In **Section 2**, we present the research design and methods and the model used to generate the PV production data. **Section 3** describes and discusses the results from which we conclude in **Section 4**.

## 2. RESEARCH DESIGN AND METHODS

We base our analysis on an hourly energy balance considering electricity consumption $c$ and PV production $p$ in the Hanover Region (Germany) using the concept of residual load. Residual load refers to the remaining electricity demand on the grid that is not met by renewable energy sources and must be supplied by conventional power generation, taking into account the intermittency of renewable generation. In mathematical terms, we express the positive residual load $rl$ as the difference between the load and production when the load is greater than the production

$$rl = \max(0, c - p)$$

Similarly, we define the negative residual load as residual production $rp$ when the production is greater than the load

$$rp = \max(0, p - c)$$

The general idea is that storages are required to shift electricity from times with residual production to times [3]with residual load. Additional components of the energy system (such as wind turbines, backup power plants) and the electricity grid are not part of the analysis.

### *2.1 PV data*

The present study uses the framework CityPV developed by Bredemeier et al. [3] to generate PV data. The software is a complete tool chain that extracts building geometries from the input data, places PV modules on each surface and calculates hourly electricity yields for the modules. **Figure 1** shows the structure of the toolchain.

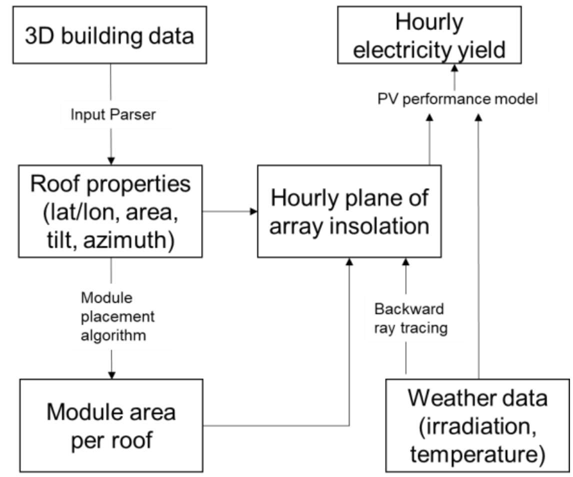


**Figure 1**: Structure of CityPV data processing

CityPV utilizes Level of Detail 2 (LoD-2) data to extract building polygons, which are crucial for creating three-dimensional meshes and calculating roof properties such as tilt, azimuth, and area. However, structural details and constraints, such as preservation orders or features like chimneys and windows, are not considered. The study also does not account for shadowing by trees, resulting in an upper limit of technical potential. Buildings are defined by one or more roofs. Unlike some studies, no roofs are excluded based on low electricity generation potential.

In the following, the roof shape is analyzed using a heuristic packing algorithm to maximize the number of photovoltaic (PV) modules that fit. The algorithm considers reductions in roof size for module spacing and explores both landscape and portrait orientations for pitched roofs, choosing the option with more modules.

The electricity yield simulation begins with calculating insolation on each roof using the isotropic transposition model, considering diffuse horizontal irradiation and the sky view factor. The latter is determined through backward ray tracing, generating a sky view map. This map enables the identification of shaded areas over the year. The electrical yield simulation employs the pvlib package [4], converting total irradiance into effective irradiance, module power, and eventually a capacity factor. The Sandia PV Array Performance Model is used, accounting for spectral losses and angle of incidence, with a DC to AC-ratio of 1.14 assumed [5].

### *2.2 Case study: Hanover Region*

We apply CityPV to the Hanover Region, which is an administrative district with a population of 1.16 Mio. people in the northern half of Germany. We determine the hourly electricity production of PV systems for each of the 828,000 roof surfaces in the Hanover Region. Using a module efficiency of 18.2 %, CityPV calculates a maximum capacity potential of 8.05 GWp and a maximum electricity generation of 6 TWh. The exploitable potential in reality will be lower due to the limitations of LoD-2 data. Our estimate is that approximately 50 % of the technical potential is actually available [6–8], which is equal to 4 GWp in the Hanover Region. To put this into perspective: the climate protection act of Lower Saxony aims at 50 GWp PV on sealed surfaces by 2035 [9]. Breaking this down to the administrative district (based on unpublished calculations of the rooftop PV potential in Lower Saxony using CityPV) would require 4 GWp on sealed surfaces in the Hanover Region.

We assume that buildings with the lowest levelized cost of electricity (LCOE) are built first. We perform our analysis over the PV deployment level between 0 and 100 %, which describes the ratio of installed capacity to maximum capacity. Thus, a PV deployment level of 50 % would roughly be equal to the maximum realizable potential. This makes the simplification that structural obstacles are only assumed on the worst 50 %, although these can actually be found on all areas.

The electricity consumption uses a synthetic load curve from Verwiebe et al. [10]. We consider two scenarios: (i) Today's scenario (called *Scenario 2023*) assumes a PV module efficiency of 18.2 % and an annual consumption of 6.0 TWh, which is an estimate for today's electricity consumption [10]. (ii) The scenario based in an emission-free future (called *Scenario 2045*) assumes a PV module efficiency of 26 % [11] (+43 % compared to 2023) and an annual consumption of 11.5 TWh (+92 % compared to 2023). The largest consumers in the *Scenario 2045* are domestic heat pumps with 3.0 TWh (equivalent to a share on the heating sector of 89 %) and BEV with 2.3 TWh (equivalent to a complete electrification of passenger road transport).

## 3. RESULTS, FINDINGS, AND RECOMMENDATIONS

**Figure 2** shows the resulting load balance for one example week in July for the Hanover Region using an aggregated view on the region as a whole under the assumption that all roofs with LCOE of less than 11 ct/kWh are built on. This is equivalent to an installed capacity of 2.7 GW or 34 % of the maximum capacity. The figure clearly shows the intermittency of the PV generation. During three of the seven days shown, PV production exceeds the electrical load during multiple hours during noon. In these hours, the region generates residual production. Nevertheless, there are multiple days where PV production is almost neglectable.

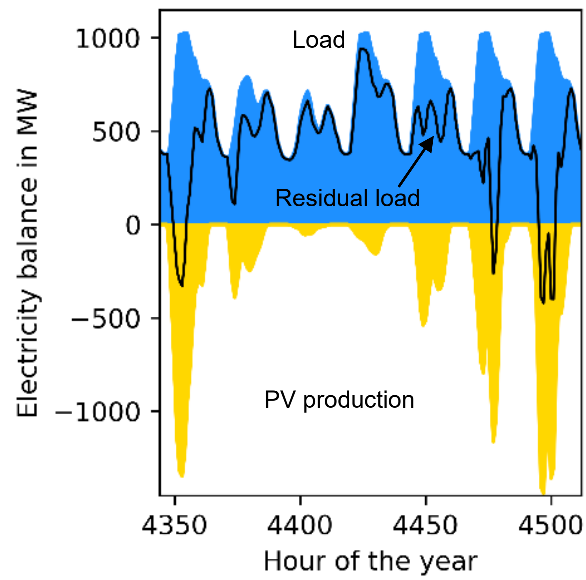


**Figure 2**: Load balance for the Hanover Region for one example week in July under the assumption that all roofs with levelized cost of electricity of less than 11 ct/kWh are built on. This is equivalent to 34 % of the maximum capacity.

### *3.1 Storage breakpoints*

**Figure 3** shows the annual residual load and PV production over the share of the developed PV potential in the maximum potential. In **Figure 4**, we plot the saldo of the daily residual load in percent of the daily consumption. From the combination of both figures, we identify certain break points of storage requirements.

At a PV deployment level of 0 %, there are no PV installations by definition and hence, the annual sum of the hourly residual load equals the annual consumption. In *Scenario 2023* until a PV deployment of 22 %, PV production can be almost entirely used for direct consumption. Here, residual PV production does not exceed 1 % of the annual consumption and the residual load decreases to 80 % of the annual consumption, which translates to a solar coverage of 20 % accordingly (**Figure 3**). Storages are not required until this point if a) flexible power plants cover the residual load and b) the distribution grid can transfer electricity from buildings with high PV production to buildings with high load. Until a PV deployment of 24 %, the saldo of every day of the year is positive, which means that the daily consumption is always higher than the daily PV production (**Figure 4**). This indicates that a storage dimensioning that enables an energy shift from PV peak production during daytime to nighttime within 24 hours is sufficient to completely use PV electricity production.

From a PV deployment of 32 % upwards, the residual PV production raises faster than the residual load declines (in other words: the gradient of residual PV production exceeds the negative gradient of residual load). At this point, the majority of electricity produced by additional PV modules is excess electricity and requires additional storages to be used (**Figure 3**). From a PV deployment of 44 % upwards, the gradient of residual PV production exceeds the gradient of residual load at least by a factor two (**Figure 3**). At the maximum realizable potential, which we estimate at a PV deployment level of 50 %, there are 69 days where the daily PV production exceeds daily consumption and the daily PV production exceeds 150 % of the daily consumption for 12 days and (**Figure 4**). Long-term storages, e.g. via the usage of hydrogen, would be required to shift energy from summer to winter season. The Hanover Region would then achieve a solar coverage of 37 % and an additional 19 % of the annual consumption can be covered by residual production using appropriate storage design (**Figure 3**). Nevertheless, there would still be 44 days where over 90 % of the daily consumption cannot be covered by PV.

Interestingly, the identified trends in the *Scenario 2023* persist in the *Scenario 2045*, due to both a higher module efficiency (resulting in both higher installed capacity and annual electricity production) and a higher electricity consumption. Residual PV production does not exceed 1 % of the annual consumption until a share of 21 % (compared to 22 % in 2023) and the gradient of residual PV production exceeds the gradient of residual load from 33 % share upwards (compared to 32 % in 2023). At a PV deployment level of 50 %, the Hanover Region would achieve a solar coverage of 28 % and an additional 14 % of the annual consumption can be covered by residual production using appropriate storage design.

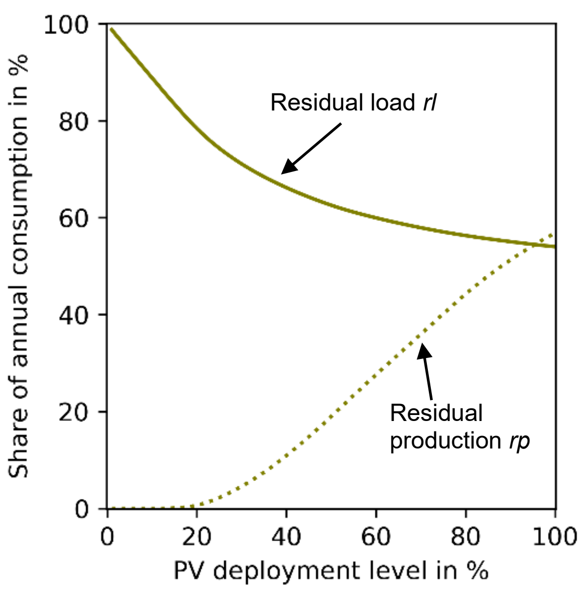


**Figure 3**: Annual sum of the hourly residual load (solid line) and residual PV production (dotted line) in percent of the annual consumption for the *Scenario 2023* over the share of the PV capacity potential in the maximum potential

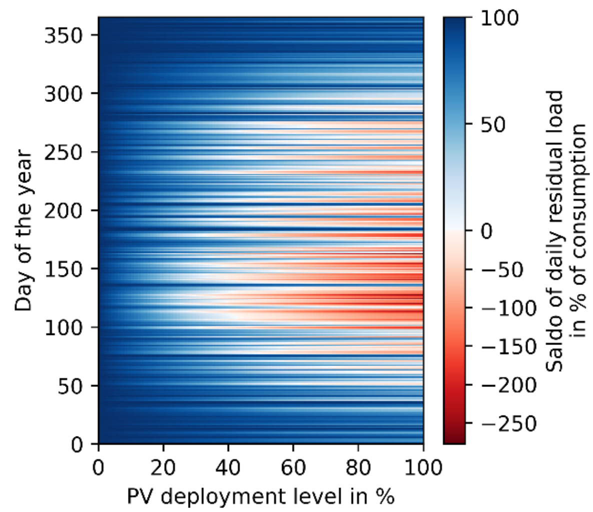


**Figure 4**: Saldo of daily residual load in percent of the daily consumption for the *Scenario 2023* over the share of the PV capacity potential in the maximum potential. For positive values, the daily consumption is higher than the daily PV production. Accordingly, for negative values, the daily PV production is higher than the daily consumption.

### *3.2 Spatial analysis*

The aggregated analysis from section 3.1 falls short in that it does not account for the necessity to transport electricity from buildings with PV to buildings without PV. Therefore, we classify the building-specific residential data of the *Scenario 2023* into the 100m-raster of the census data [12]. We use the ALKIS-codes [13] 31001_1000 (residential buildings), 31001_1210 (agricultural and forestry residential building), and 31001_1120 (residential buildings with retail and services) for residential buildings and the residential load profile from Verwiebe et al. [10]. We use the correlation between population density and electricity consumption similar to [14] to distribute the residential electricity consumption into the 1ha cells. Residential buildings in the Hanover Region have a higher ratio of possible PV production to consumption than the region as a whole: as we described in section 2.2, the region as a whole has an electricity consumption of 6 TWh and a potential PV production of 6 TWh (at a theoretical PV deployment level of 100 %). In contrast, residual buildings have an electricity consumption of 1.8 TWh and a potential PV production of 2.8 TWh.

In **Figure 5** and **Figure 6**, we show the annual electricity balance of each cell, where positive numbers denote a higher annual consumption (consumption cells) and negative numbers denote a higher annual PV production (surplus cells). In **Figure 7** and **Figure 8**, we show the minimum of the annual sum of residual load and residual consumption min(*rl*, *rp*) as a percentage of the median consumption per cell, which is 40 MWh. According to our definition, cells with a high residual load and production where min(*rl*, *rp*) is large have high balance requirements, as storage systems allow residual generation to be shifted to times with residual load. If at least one of the two values of *rp* and *rl* is small, min(*rl*, *rp*) is also small, so that cells in this case no longer have high balance requirements. We define cells where min(*rl*, *rp*) is less than 10 % of the median consumption as cells with little balance requirements and color them green in **Figure 7** and **Figure 8**. In similar fashion, we classify cells into the categories between 10 and 50 % of the median consumption, 50 to 100 % of the median consumption and more than 100 % of the median consumption.

We define urban cells as cells with a population density of 39 or more people per ha, following the definition of the city of Hanover [15]. Accordingly, rural cells are cells with a population density of less than 39 people per ha. This leads to a split of 29 % urban cells and 71 % rural cells in the Hanover Region.

At a PV deployment level of 22 %, 39 % of the cells are surplus cells (**Figure 5**). These cells are mainly located in rural regions of the Hanover Region, while the urban city with high population shows consumption cells primarily. Overall, 36 % of rural cells and only 12 % of urban cells are surplus cell. The mean residual consumption is 5.2 MWh for rural cells and 59.8 MWh for urban cells. At the same time, urban cells show the highest balance requirements, where 13 % of urban cells have both residual production and load higher than 100 % of the median consumption (**Figure 7**). In contrast, there is not a single rural region with high balance requirements, while the majority of cells (56 %) have low balance requirements. In total, 40 % of cells show balance requirements for more than 10 % of the median consumption and 9 % of cells show balance requirements for more than 50 % of the median consumption.

At a PV deployment level of 50 %, 80 % of cells are surplus cells (**Figure 6**). The distribution is very one-sided: rural regions are almost entirely surplus cells with a share of 84 %. In contrast, 47 % of urban cells are still consumption cells. Rural cells now on average become net producers with a mean residual production of 21.7 MWh per cell, while urban cells are still net consumers with a mean residual consumption of 3.6 MWh. This shows a clear necessary direction of electricity transport from rural into urban regions. Balance requirements are generally higher with increasing levels of PV deployment. Two thirds of cells have medium or high balance requirements, but the distribution is still very one-sided: 33 % of urban cells and still not a single rural cell shows high balance requirements (**Figure 8**).

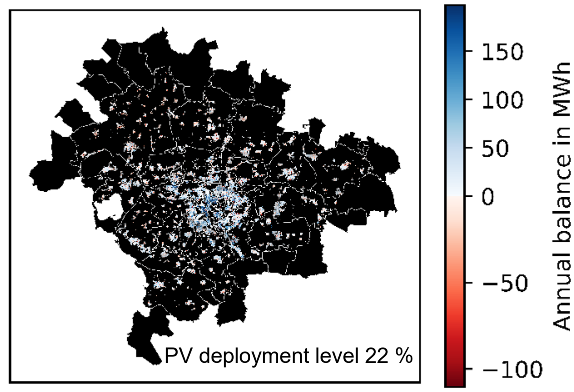


**Figure 5**: Annual balance of electricity production of residential data in a 1 ha resolution. Values shown for a PV deployment level of 22 %. Positive numbers denote a higher annual consumption while negative numbers denote a higher annual PV production.

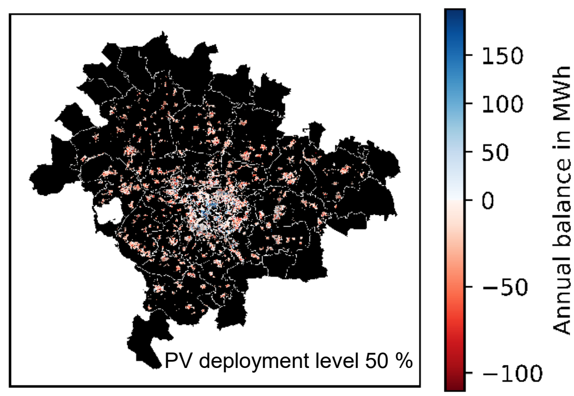


**Figure 6**: Annual balance of electricity production of residential data in a 1 ha resolution. Values shown for a PV deployment level of 50 %. Positive numbers denote a higher annual consumption while negative numbers denote a higher annual PV production.

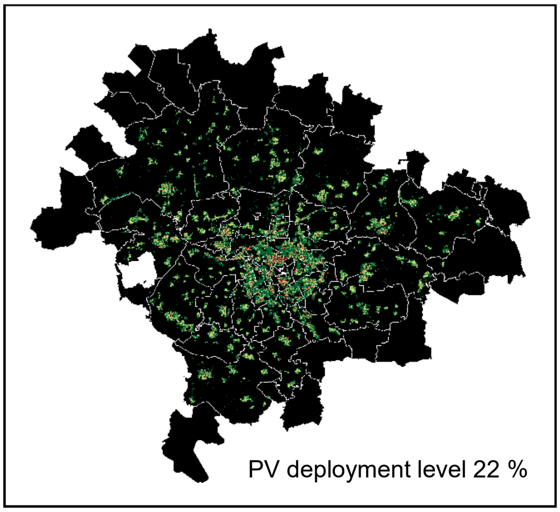


**Figure 7**: Balance requirements in a 1 ha resolution defined as min(*rl*, *rp*). Values shown for PV deployment levels of 22 %. Balance requirements defined as low (< 10 % of median consumption, green), medium (10 to 50 %, yellow and 50 to 100 % of median consumption, orange) and high (> 100 % of median consumption, red). The median consumption is 40 MWh.

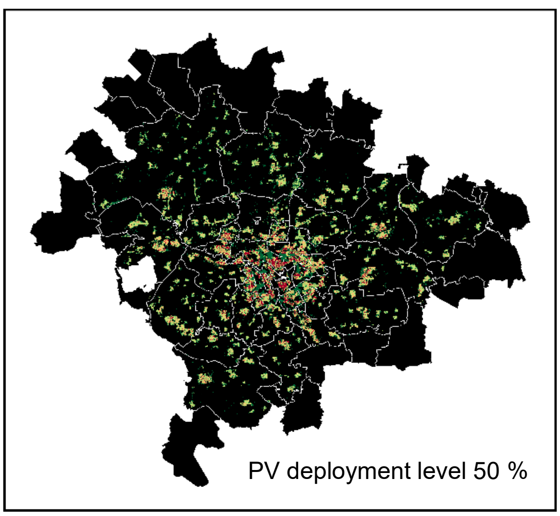


**Figure 8**: Balance requirements in a 1 ha resolution defined as min(*rl*, *rp*). Values shown for PV deployment levels of 50 %. Balance requirements defined as low (< 10 % of median consumption, green), medium (10 to 50 %, yellow and 50 to 100 % of median consumption, orange) and high (> 100 % of median consumption, red). The median consumption is 40 MWh.

From our observations, two trends become visible: First, urban city centers with high shares of residential buildings will not able to supply even their current electricity consumption at a maximum realizable PV deployment level in an annual balance. At the same time, rural regions will increasingly generate excess electricity and the amount of load centers nearby diminishes with higher PV deployment levels. Second, despite their high electricity consumption in an annual balance, urban city centers show large balance requirements as soon as considerable amounts of PV are installed whereas rural cells never reach high balance requirements due to their low consumption density. This contradicts the current real world development: An analysis of the German market master data register (Marktstammdatenregister) [16] shows that the installed storage power is inversely correlated to the share of urban cells, which we plot in **Figure 9**. The share of urban cells is the number of urban cells divided by the number of all cells per postcode area. Urban centers currently show neglectable amounts of storages while the vast majority of storage power is installed in the hinterland. If this trend continues, urban regions would cause high transportation needs, with large electricity exports during peak PV production and large electricity imports during night and winter.

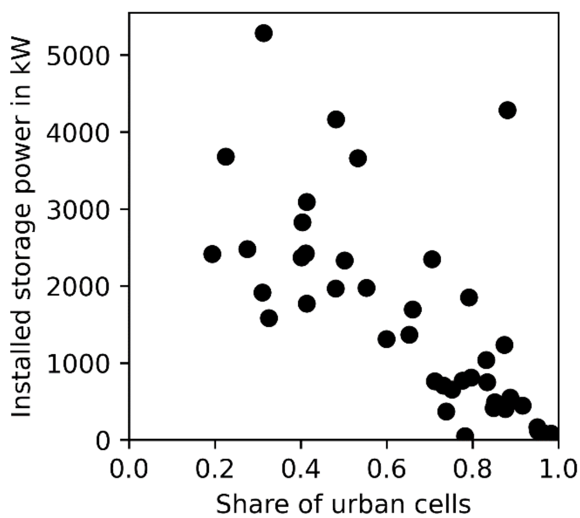


**Figure 9**: Installed storage power over the share of urban cells per postcode in the Hanover Region as of the end of 2023. This excludes the postcode of Herrenhausen (storage power of 16398 kW and share of urban cells of 0.87) for visibility reasons.

## 4. CONCLUSIONS

We presented an analysis of future storage requirements for the integration of rooftop PV into urban energy systems using a case study of the Hanover Region, a partly rural region with the city of Hanover at its center. The ambitious climate goals of Hanover's federal state Lower Saxony necessitate the deployment of PV panels on the vast majority of rooftops by 2035. The integration of decentralized energy sources poses, however, a complex challenge as cities continue to install more and more rooftop photovoltaic systems.

Using the concept of residual load and residual production, we identified breakpoints of storage requirements. At 100 % of the realizable capacity, the region can achieve a solar coverage of 37 % and can supply an additional 19 % of its annual consumption from PV using appropriate urban storages. Large levels of PV deployment (> 40 % of realizable capacity) are possible with only minimal residual PV production in the region as a whole, without considering wind energy.

Additionally, our analysis reveals that urban regions with high population density show the largest balance requirements with both high residual load and high residual production. In contrast to these findings, the actual deployment of battery storage systems in the real world demonstrates an inverse relationship between urbanity and installed storage capacity. This underlines the importance of providing incentives for the construction of PV systems and decentral battery storage systems in rented apartment buildings, which are predominantly found in urban centers. Rural regions are positioned to become net electricity producers, necessitating adequate transmission infrastructure to funnel the electricity into urban areas.

## AUTHORS' CONTRIBUTIONS

**Marlon Schlemminger**: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Visualization **Dennis Bredemeier**: Software, Writing – Review & Editing **Alexander Mahner**: Writing – Review & Editing **Raphael Niepelt**: Writing – Review & Editing, Supervision, Project administration, Funding acquisition **Michael H. Breitner**: Writing – Review & Editing, Supervision, Project administration, Funding acquisition **Rolf Brendel**: Resources, Writing – Review & Editing, Supervision, Project administration, Funding acquisition

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