

Article

Potential Analysis of Hybrid Renewable Energy Systems for Self-Sufficient Residential Use in Germany and the Czech Republic

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Abstract: Independence from the power grid can be pursued by achieving total self-sufficient electricity supply. Such an energy supply model might be particularly interesting for settlements located in rural areas where enough space is available for energy generation installations. This article evaluates how and at what cost electricity demand of residential users across Germany and the Czech Republic could be covered by hybrid renewable energy generation systems consisting of photovoltaics, micro-generation wind turbines and batteries. High-resolution reanalysis data are used to calculate necessary system sizes over a large area by simultaneously accounting for the temporal variability of renewable energy. For every potential location in the research area, the hybrid system requirements for clusters of 50 self-sufficient single-family houses are calculated. The results indicate no general trend regarding the size of the respective technologies, although larger areas where PV-wind power complementarity enables lowering the total system costs and required storage capacities were determined. Assuming that the cluster of households could be constituted and depending on the location, the total installation and operation costs for the proposed systems for a lifetime of 20 years range between EUR 1.8 Million and EUR 5 Million without considering costs of financing. Regions with the lowest costs were identified mainly in the south of Germany.

Keywords: renewable energy; COSMO-REA6; electric storage systems; residential electric demand clusters; hybrid renewable energy system sizing; spatiotemporal modelling

1. Introduction

Buildings continue to exceed 40% of the primary energy consumption in most countries [1]. The awareness is rising, that this demand needs to be covered by sustainable energy sources in order to reduce CO₂ emissions. The enormous technical improvements of renewable energy generation technologies and the thereof corresponding cost reductions in recent years, have made renewable energy systems an attractive solution to locally produce and provide clean electricity [2]. More than 21 GW of Photovoltaic (PV) generation capacity from installations smaller than 20 kW in Europe until 2017 [3] prove the feasibility and positive response of this solution. Modern systems combining solar energy and electrical storage are able to supply large parts of the common residential electricity demand and are thus a well-established modernization measure among homeowners [4]. Nevertheless, there is an ongoing reduction of current support policies in several countries. The key question of the

EU, under which conditions residential renewable energy generation could be increased, remains to be unsolved.

Micro-scale renewable power generation systems for residential buildings are typically aiming at minimizing overall system cost [5] and can generate energy beyond the total yearly consumption. However, due to the intrinsic variability in the availability of renewable energy sources, in order to achieve full electricity self-sufficiency at any given time, considerably larger installed capacities are necessary compared to systems that rely on the grid to compensate periods of excess or insufficient renewable generation [6]. This is the reason why stand-alone power systems are mainly conceived as an off-the-grid electricity solution for locations that are not connected to an electricity distribution system, particularly islands or remote rural areas where grid extension costs are unfeasibly high [7]. In a context of accelerating urbanization resulting in a population decline in rural areas while increasing the number of sparsely populated regions in the decades ahead [8], the costs of maintenance of the electrical grid per capita will increase and electricity self-sufficient settlements could become an economically feasible alternative.

The optimal configuration of renewable hybrid energy systems for self-sufficient houses and communities is a challenging exercise. The optimal combination of energy generation technologies and storage is depending on factors such as spatial and temporal availability of renewable energy sources, prevailing weather, technical possibilities and legal restrictions, energy demand and, more specifically, load profiles as well as financial means of the initiators [9]. Preceding studies have examined diverse aspects of optimal installations and locations. For instance, Weniger et al. [10] simulated the optimal system configuration for a single family House (SFH) in Berlin, considering several levels of self-sufficiency. In their assessment, the authors used temporally highly resolved solar radiation data derived from several reference years in combination with residential load time series on a temporal scale of one minute. Although their results are optimistic regarding the feasibility and applicability of full self-sufficiency, the simulation focuses on a single location. It was not elucidated to which extent such results could be affected by differences among regions. Hoppmann et al. [11] assessed the economic feasibility of self-sufficient households in Stuttgart using eight retail and wholesale price scenarios in combination with different types of PV and battery systems. Nižetić et al. [12] evaluated multiple configurations of hybrid systems in detail, putting emphasis on the heat/cooling demand of buildings and making use of solar resources, but only for one specific geographical location. Regarding demand profiles, Widén et al. [13] studied the potential of demand side management to approximate PV generation to residential load of individual buildings in Stockholm. Other studies investigated technical characteristics of various battery sizes [14,15], focusing on different spatial scales, from individual buildings up to municipalities. Considerable research efforts concerning the ideal configuration of such hybrid systems using wind and solar power exist for particular locations (see e.g., [16–18]). These studies focus on the techno-economic feasibility of a hybridized energy system and consider different optimization algorithms [16], demand response strategies [17], system net present costs or costs of energy generation [18] among others. The studies observed, however, vary in the spatial and temporal resolution as well as their methodological approach. This complicates comparisons and a generalization of results.

There still exist various reviews on PV and wind hybrid systems, e.g., Al-falahi et al. [19], Khare et al. [20], Anoune et al. [21] and Kahn et al. [22]. Following their findings, it is possible to state that only a minority of the studies about self-sufficient buildings or settlements address multiple locations. Billir et al. [23] are one of these exceptions simulating the required electricity supply for a detached house in five major cities in different European climate zones. Another comparative study was conducted by Quoilin et al. [24], who looked at the economic feasibility of battery systems powered by solar power. They simulated these systems for several EU countries with the aim to maximize their electricity self-consumption. However, data on irradiance was only available for single locations in the different countries not accounting for climatic differences within a country. This is the reason why their respective conclusions cannot simply be applied to the rest of their research area.

Furthermore, there are also multiple articles addressing large geographical areas and climate differences between regions, analyzing electrical systems on a regional or country basis. Killinger et al. [25] identify optimal locations for solar and wind power plants with the objective that their generation meets specified conditions of efficiency and stability, defying the natural variability of renewable resources [26]. Their calculation was executed for every NUTS3-Region in Germany using the COSMO-DE reanalysis dataset. It has an original temporal resolution of one hour and a spatial resolution of approximately 2.8 km by 2.8 km. The authors summarized irradiation data, prevalent wind speeds and temperature data for the NUTS3-regions for each time step. This leads to a simplification that might neglect differences in the availability of resources within the NUTS3-regions, which could especially affect results in mountainous regions. Zappa and van der Broek [27] analyze the potential in the EU to integrate different types of wind and solar power technologies using ERA-Interim data [28] and an optimization model minimizing residual demand. Furthermore, it is only found in studies assessing the mere complementarity of wind and solar power, that attention is given to cover large geographical areas in a high spatial and temporal resolution. For instance Monforti et al. [29] assess complementarity of the output of PV and wind power installations for entire Italy in a 4 km by 4 km spatial resolution using hourly data from the year 2005.

Considering these findings, we observe an existing gap of knowledge in several specific aspects:

- While there are several studies on PV or PV-battery systems [4,10,11,13–15,24,30], the investigation of self-sufficient hybrid systems (solar and wind energy combined with electrical storage) for residential use are scarce.
- Many of the studies are mostly based on environmental data (wind speeds, solar irradiation) of single locations [16–18] not accounting for local long- and short-term availability and intermittency of natural resources, which are crucial to sustain self-sufficiency at all times. Furthermore, these studies usually neglect the potential of harnessing complementarity of wind and solar resources to decrease total system costs while increasing efficiency, stability and reliability of electricity generation [16,25]. Studies on larger regions [25,27], however, imply connection to the grid and therefore do not apply to the concept of self-sufficiency of sparsely populated regions in the future, but at the aim of maximizing self-consumption or minimizing residential load.
- While in other studies, analyses were based on data of high temporal resolution, e.g., per minute [10], spatial resolution is generally low in the existing literature or the analysis is restricted only to single sites or smaller areas such as cities [10,11,13,16–18,27] or single NUTS-3 regions [25], reducing conclusions about applicability of investigated systems only to limited locations. In order to be of use to political and planning stakeholders, however, it is necessary to be able to compare sites covering larger regions in a high spatial resolution considering local resource availability. This can act as a decision-making basis for finding optimal locations and planning as well as investing accordingly. Studies covering large geographical areas with high spatial and temporal resolutions can be found only for assessments of complementarity of wind and PV power generation and not for hybrid systems sizing and costs.

Therefore, with the present study, we aim at investigating the potential of hybrid renewable systems to supply electricity to clusters of households by conducting a comprehensive analysis in rather sparsely populated areas in Germany and the Czech Republic. Our method takes into account sufficient data with high spatio-temporal resolution to be able to address local conditions in every single section of a large geographical area. We are seeking to show the potential of supplying especially rural areas with sustainable and secure energy.

To the best of our knowledge, only in [30], the minimum battery and PV requirements for self-sufficient single family houses are evaluated by also accounting for a large geographical area and the climate differences of multiple locations. A first preliminary attempt to extend this study by additionally considering wind power and larger residential users was presented in [31]. Here, the potential complementarity of wind and solar power to reduce total costs of the systems was studied

for clusters of 10 SFHs in Germany and the Czech Republic. In this present study, we considerably extend the efforts of [31] by running additional scenarios with larger cluster sizes. We evaluate the large set of results including a cost-assessment to identify the areas in the two countries that would best be suited for the installation of such hybrid systems and show where harnessing the complementarity between wind and solar resources is possible. The present assessment is taking the recently published high-resolution ($6\text{ km} \times 6\text{ km}$) regional (Central Europe) reanalysis data (COSMO-REA6) into account. Additionally, we derive the electricity generation potential of PV and wind turbines. The study is conducted with spatially explicit population data at 1 km^2 resolution. With this, we address the high variability in cluster potentials of SFH on the one hand, and on the other hand focus on the spatial variability of possible locations for renewable power generation. The model is developed as a mixed integer linear optimization model (MILP) with the main objective to minimize total system costs under technical and economic constraints resulting in the required installation sizes of wind, PV and battery systems. Resulting configurations are presented in figures which are based on requirements for clusters of 10 and 50 single-family houses in low population density areas assuming these areas would be in general more eligible for such discussed systems compared to buildings in urban areas due to space availability for installations.

The present article is structured as follows: In Section 2, we present the methodology consisting of the data used in our approach, the steps to calculate the demand, a detailed description of our proposed hybrid PV-wind-battery system, the MILP and the scenarios that we developed. We present our results and discuss them in Section 3, both from a spatial and temporal perspective. The analysis highlights the relevance of snow cover and how the storage requirements of the system depend on short weather events concentrated in time. Maps of the research area in Germany and the Czech Republic make the spatial distribution of the hybrid systems visible. Finally, after comparing our results to existing literature, conclusions are drawn in Section 4.

2. Materials and Methods

The methodology consists of four subsequent steps. First, spatiotemporal datasets including PV and wind power potentials were generated with technical PV and wind installation models relying on COSMO-REA6 data (Section 2.1). Second, we use standardized load profiles of residential households obtaining electricity demand time series for rural and low-density-populated urban areas (Section 2.2). Third, these datasets are input to a mixed-integer linear program (MILP) which calculates the optimal number of wind power installations and PV and battery system sizes. The MILP solves for the main objective of minimizing total system costs while ensuring electricity self-sufficiency (Section 2.3). The model is applied to all regions in Germany and the Czech Republic on a spatial resolution of 1 km^2 focusing on areas which have a low population density. Fourth, the proposed MILP is used to calculate scenarios with the characteristics described in Section 2.4.

The methodology is sketched in Figure 1. The hybrid electricity system consists of clusters of 10 or 50 SFHs which are equipped with PV modules, micro-generation wind turbines with 10.5 kW capacity each and a battery storage system.

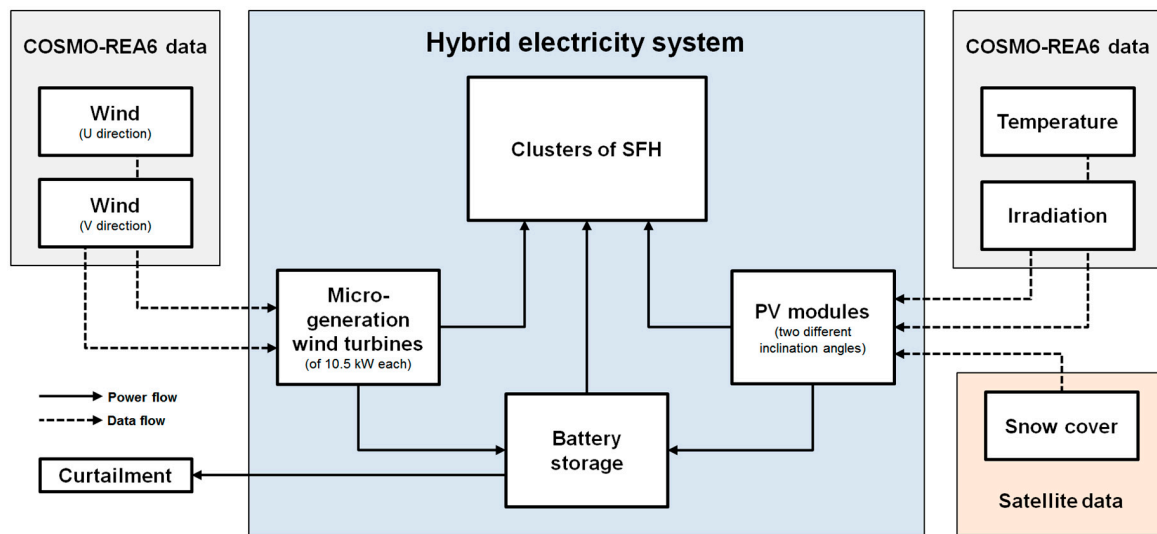


Figure 1. Schematic outline of the methodology and the data sets used.

2.1. Electricity Generation from PV and Wind Turbines

Electricity in the hybrid system is provided by wind and PV power installations. The model relies on COSMO-REA6 datasets which are made accessible by the German Meteorological Service (Deutscher Wetterdienst—DWD) [32,33]. These datasets provide high-quality information with high spatial and temporal resolution. They contain hourly time series for the years 1995 to 2015 with a spatial resolution of $6 \text{ km} \times 6 \text{ km}$. Due to their consistency, they are highly convenient and accessible inputs for energy system modelling purposes. The data is prepared for modelling by merging the monthly data sets into yearly time series and clipping them to the research area by using the Climate Data Operator—CDO [34].

Table 1 and Figure 1 show the five different variables from the COSMO-REA6 reanalysis datasets that were used for the wind and PV power calculations. The solar irradiation data and the prevalent wind speed data calculated on the basis of these variables were already validated in [35,36]. Wind speeds at 10 m height are derived from the U_{10M} and V_{10M} variables of the COSMO-REA6 dataset. As input, we use a generic power curve of a micro-generation wind turbine that has a nominal power output of 10.5 kW, which is modeled according to the technical specifications of three similar wind turbines [37,38]. Equation (1) describes the wind power output (wp) depending on a certain wind speed (ws). According to this equation, the wind power is interpolated from wind speeds between given values of the power curve: The closest wind speed values on the power curve below (ws_{lo}) and above (ws_{hi}) each hourly wind speed (ws) are used. Their corresponding wind power generation output (wp_{lo} and wp_{hi}) is determined from the power curve and linearly interpolated to an hourly wind power output (wp).

$$wp = \frac{(wp_{hi} - wp_{lo}) \times ws + ws_{hi} \times wp_{lo} - ws_{lo} \times wp_{hi}}{ws_{hi} - ws_{lo}} \quad (1)$$

Regarding PV power, the two variables $SWDIFDS_RAD$ and $SWDIRS_RAD$ account for the downward diffuse short-wave radiation flux and the downward direct short-wave radiation flux at surface level respectively. Additionally, the ambient temperature at two-meter height (T2M) is an input variable for the model extracted from the COSMO-REA 6 datasets. The additional use of a dataset from the Land Surface Analysis Satellite Applications Facility (LSA-SAF) [39], includes snow covers (SC) [40,41] and allows to consider the effects of reduced PV generation through snow-covered modules in the winter months. Applied algorithms and validation processes of the SC data are described in [42]. Following Wirth et al. [43], the LSA-SAF SC datasets are excellent for solar energy modelling purposes. The SC dataset contains information since 2007 at $3 \text{ km} \times 3 \text{ km}$ resolution and describes the level of

snow cover by the categories “totally snow covered”, “partially snow covered”, “snow free ground” as well as “unclassified”, “water” and “non-processed”.

Table 1. List of the spatiotemporal data required for the renewable electricity generation potential evaluation.

Source	Type of Product (Variable Name)	Provider	Spatial Resolution	Temporal Resolution	Unit	Data Format
COSMO-REA6	Downward diffuse short-wave radiation flux at surface (SWDIFDS_RAD)	DWD	6 km × 6 km	1 hour	W/m ²	GRIB
COSMO-REA6	Downward direct short-wave radiation flux at surface (SWDIRS_RAD)	DWD	6 km × 6 km	1 hour	W/m ²	GRIB
COSMO-REA6	Ambient temperature at two-meter height (T2M)	DWD	6 km × 6 km	1 hour	K	GRIB
COSMO-REA6	Wind velocity at 10 m above ground, u direction (U_10M)	DWD	6 km × 6 km	1 hour	m/s	GRIB
COSMO-REA6	Wind velocity at 10 m above ground, v direction (V_10M)	DWD	6 km × 6 km	1 hour	m/s	GRIB
Satellite images MSG	Snow Cover (SC)	LSA-SAF	3 km × 3 km at nadir	15 min	Classification in integer values from 0 to 5	HDF5

For calculating the global in-plane radiation and consequently the PV power generation, PVLIB [44], a python library especially developed for simulating the performance of PV systems, was used. Two different inclination angles are defined to assess the reductions in PV power generation due to snow cover. The first angle (PV1) is always set to the latitude of the particular raster pixel itself, which corresponds to an approximation of the optimal position for a maximum solar power generation throughout the year. This means, that in scenario PV1, every raster pixel is set to its own optimal inclination. Alternating, the second angle (PV2) is set at 70° inclination, which should ensure snow-free PV modules and therefore higher PV generation during the winter months [45], although limiting the power generation during the year due to the sub-optimal positioning of the module.

For the calculation of the potential PV power output, Equation (2), that is also included in the PVLIB library [44], was used. The resulting $pvOutput_{t,a}$ is a time series of hourly expected PV power output and is separately calculated for the two previously defined angles of inclination (PV1, PV2). It is conservatively assumed, that no PV power generation is possible with the PV1 setup at hours where snow cover is recorded, due to either fully or partially snow-covered panels. The ambient air temperature T_t^{amb} is defined by the T2M data, which is also part of the COSMO-REA6 dataset.

$$pvOutput_{t,a}(G) = G \times \eta_{PV} \times \left[1 + \alpha_{PMPP} \left((T_t^{amb} + k_T G / A) - T_0 \right) \right] \quad (2)$$

$pvOutput_{t,a}$ is the power output of the PV modules per kWp at time t [W]; G is the GHI derived from the calculations using PVLIB and COSMO-REA6 data [W/m²]; η_{PV} is the total efficiency of the PV panels, which is set to 21% for the present analysis; α_{PMPP} is a temperature correction factor, in this case set to a constant equal to −0.0045 [1/°C]; T_t^{amb} is defined as the ambient air temperature from COSMO-REA6 data [°C]; k_T represents the reduction factor of power generation due to the installation type [°C/(W/m²)], in this case it is set to 0.05; A is the total area of all installed PV modules in [m²] and T_0 is the nominal operating temperature [°C], which is set to 25 °C.

2.2. Identification of Potential Locations and Energy Demand

Although, due to data availability, the PV and wind potential could theoretically be calculated for the whole of Europe, the present analysis was restricted to certain regions for two reasons. On the one hand, the study is conducted as part of the project CrossEnergy, which is a cross-border project in Germany and the Czech Republic [46]. Therefore, only areas within administrative boundaries of these two countries were considered in the analysis. On the other hand, only pixels with “intermediate density areas” and “thinly populated areas” [47] were included in the analysis. This classification follows the degree of urbanization as per EUROSTAT and comprises areas with less than 1500 inhabitants per square-kilometer, which are the regions where most SFHs are constructed. In order to conduct this classification, data on population density obtained from the project LUISA published by the European Commission [8] are used. This dataset includes, among others, the number of inhabitants per square kilometer in 2010 as well as population development projections for the years 2020, 2030, 2040 and 2050 for Germany and the Czech Republic.

Following the methodology presented in [30], standardized quarter-hourly load profiles provided by the Association of the German Energy and Water Industries (Bundesverband der Energie- und Wasserwirtschaft - BDEW) are scaled to the yearly electricity demand of households (Germany: 3079 kWh/a and the Czech Republic: 3064 kWh/a [48]) and aggregated hourly to match the temporal resolution of the electricity generation data. Since we consider multiple SFHs, we scale the electricity demand of one household, so that we get load profiles for clusters of 10 and 50 SFHs. Adopting the methodology from [30] enables a comparison of self-sufficient households with PV-battery systems (as published in [49]) to PV-wind-battery systems and an assessment of the benefits of including also wind energy in such systems.

2.3. Mixed Integer Linear Program to Size Hybrid PV-Wind-Battery Systems

The MILP used in this paper is based on the approach introduced in [30], where a PV-battery system was sized for Electricity Self-Sufficient Single Family Houses using a linear program, but was extended for additional key components. The recent version adds small-scale wind power generation systems. The main objective function described by Equation (3) is aiming at minimizing the systems total installation costs by varying sizes of kWp PV ($pvSize_a$) and kWh battery ($esSize$) systems as well as the number of wind turbines ($windSize$) and their respective installation costs per kWp of PV ($pvCost$), per wind turbine ($windCost$) and per kWh of battery storage ($esCost$). The lifetime of the battery is accounted for by a replacement factor, $esReplace$ (equal to 2 for a 20-year lifetime).

$$\min \left(pvCost \times \sum_a pvSize_a \right) + (windCost \times windSize) + (esSize \times esCost \times esReplace) \quad (3)$$

In order to accomplish the prerequisite of electricity self-sufficiency, four balancing conditions are necessary. The first condition, equation 4, describes the relationship between electricity supply and demand. This means that demand has to be covered at all times only by PV and wind power electricity produced in the simulated time period or by electricity from the storage.

$$eDemand_t = ePVUse_t + eWindUse_t + eStorDischarge_t \times eStorDischargeEff, \forall t \quad (4)$$

$eDemand_t$ is the hourly electricity demand of a cluster of households, while $ePVUse_t$ and $eWindUse_t$ refer to the amount of PV and wind electricity that are directly used per hour. $eStorDischarge_t$ accounts for electricity needed from the storage system in order to meet the demand at any given time. Extracting energy from the storage implies losses which are accounted for by the storage discharge efficiency $eStorDischargeEff$, that is assumed to be a constant factor.

The second balancing condition refers to wind energy generation split into direct use per hour ($eWindUse_t$), a part that is stored each hour ($eWindStore_t$), and the rest which can neither be used nor

stored, the so-called curtailment ($windSurplus_t$). The wind power output is calculated by multiplying the number of turbines at each location with the output of one turbine derived from the reanalysis wind speeds for each hour ($windOutput_t$):

$$\sum_a (windSize_a \times windOutput_{t,a}) = eWindUse_t + eWindStore_t + windSurplus_t, \forall t \quad (5)$$

The third condition for balancing is analogous to the previous one for wind energy generation and implies that hourly PV generation (size of the PV system in kWp in a location multiplied by the output of one kWp PV ($pvOutput_{t,a}$)) must equal the sum of PV electricity for direct use ($ePVUse_t$), storage ($ePVStore_t$) and curtailment ($pvSurplus_t$).

$$\sum_a (pvSize_a \times pvOutput_{t,a}) = ePVUse_t + ePVStore_t + pvSurplus_t, \forall t \quad (6)$$

The fourth and final balancing condition defines the state of charge of the electric storage system ($eSOC_t$). The storing efficiency ($eStoringEff$) accounts for losses over time from self-discharge, the charging efficiency ($eStorChargeEff$) for losses during the charging process. The state of charge is obtained from the sum of the state of charge in the previous time step, stored energy from PV and wind power, decreased by the energy extracted for use ($eStorDischarge_t$), while considering losses of storing and charging:

$$eSOC_{t+1} = eStoringEff \times eSOC_t + eStorChargeEff \times (ePVStore_{t+1} + eWindStore_{t+1}) - eStorDischarge_{t+1}, \forall t \quad (7)$$

In the model, $eStorDischarge_t$ is limited by the state of charge of the battery in $t - 1$ and the condition that $eSOC_t$ must not be negative. Furthermore, the first- and last-time steps in a year are assumed to be equal in order to create a periodic system. The highest $eSOC_t$ achieved during the modelled year determines the necessary storage system capacity ($esSize$):

$$eSOC_t \leq esSize, \forall t \quad (8)$$

Additional constraints for $ePVStore_t$, $eWindStore_t$, $eStorDischarge_t$ limiting the charging and discharging speed due to technical constraints ($eCapLimit$) are defined by:

$$ePVStore_t + eWindStore_t \leq eCapLimit, \forall t \quad (9)$$

$$eStorDischarge_t \leq eCapLimit, \forall t \quad (10)$$

2.4. Scenario Assumptions

The year 2010 was selected as a worst-case scenario as it was the year with the lowest total solar irradiation available in the COSMO-REA6 dataset between the years 1995 until 2015. In general, the global horizontal irradiation (GHI) in 2003 (the year with the highest GHI) was 26% higher than in 2010. Additionally, in 2010, snow cover was significantly more often recorded than in the other years of the accessible observation period. This assumptions allow a direct comparison with scenarios published in [49] where system sizes for self-sufficient households were calculated but only for battery and PV systems.

The prices of the system components are essential for the systems' overall profitability and consequently also for the optimization program. The prices are fixed and calculated in Euros; the assumptions for the system costs are based on [30,31]. For PV this results in installation costs of 2100 EUR per kWp. The battery storage system is modelled with 1000 EUR per kWh for a life-time of 10 years meaning that a replacement of the battery system is necessary for the second half of the simulated time period. The battery is operated at a round trip efficiency of 75% and a self-discharge

rate of 0.01% per hour. The investment costs of a micro-generation wind turbine modeled in this paper are averaged from market price estimations of turbines in the same category also listed in [50]. Based on this market research, costs of 56,000 EUR per 10.5 kW turbine, already including the turbine itself, installation and operational costs for service and maintenance of 2.5% for 20 years are assumed. For simplification reasons, all considered costs are averaged values and do not consider regional or country specific differences of e.g., installation costs and maintenance.

Since a single micro-generation wind turbine would already significantly exceed the required electricity demand of a single residential building, we looked at clusters of ten and fifty households. The optimization problem is solved using the CPLEX solver in a GAMS-Python [51,52] implementation.

3. Results and Discussion

The results of the optimization model for 50 SFHs are shown in Figure 2 using maps for the individual system components, namely the battery size, PV1 sizes, PV2 sizes and the number of wind turbines. The results for 10 SFHs are not exactly 1/5 of the results for 50 SFHs due to the integer condition of the wind turbines but are very close. The general considerations that can be made with both sets of results are the same. This is the reason why only the results for 50 SFHs are shown here (the results for 10 SFHs in the scenario without SC can be found in [31]). The 2 top rows show the scenario when snow cover is excluded, whereas the bottom rows includes electricity yield reductions due to snow cover. This allows a direct comparison of the effect that snow cover has on the required size of the system components. We can observe that battery system sizes are about four times larger in the region of Prague (Czech Republic) compared to several regions in Germany. This can be explained by the low complementarity between solar and wind resources in this region, which are shown as green areas in Figure 3. Regarding PV modules, the optimization model yields a higher application of PV1 when snow cover is not taken into account, which can be explained by the overall yearly higher power output of PV1 compared to PV2. However, this is just a hypothetical scenario, as the panels of type PV1 will be covered in case of snowfalls. The situation is different when the effects of snow cover are introduced in the scenario. Then a partial substitution of PV1 by PV2 can be observed. Overall, the PV1 and PV2 necessary installed capacities are only slightly larger than in the scenario excluding snow cover.

When considering the number of necessary micro-generation wind turbines, it is possible to identify a large region, mainly in the eastern part of Germany and some minor clusters near Dortmund and the east of Rostock, which would need up to 25 turbines. However, there are large parts in Bavaria where only small numbers or even no wind turbines are recommended to be installed, caused by low wind and high solar resources. This is also reflected in Figure 3, where areas of higher installed wind power capacity show a high complementarity of wind and solar resources, whereas in areas with no wind turbines installed, wind and solar irradiation indicate no complementarity. In general, the number of wind power turbines does not significantly differ between the scenarios including or excluding snow cover. This is an interesting finding as it identifies small wind turbines as a secondary generation source in areas where complementarity between wind and solar resources on a monthly basis can be identified. The missing generation capacities because of SC limiting PV generation are compensated using the PV technology with a 70° inclination and hardly by supplementary wind turbines. It is also important to note that differences between the monthly correlation based on the availability of resources (left side of Figure 3) and the one based on the output of the systems (right side of Figure 3) differ by up to ± 0.75 percentage points. This also shows the clear necessity of studies evaluating complementarity of solar and wind in renewable energy systems to actually use the electrical output of systems and not only the resources availability as an indicator. The results presented in the right side of Figure 3 are of the same order as the results presented by Monforti et al. [29] in the assessment of complementarity of PV and wind power that they performed for Italy. These authors find the highest complementarity in the monthly data also achieving best correlation values around -0.75 .

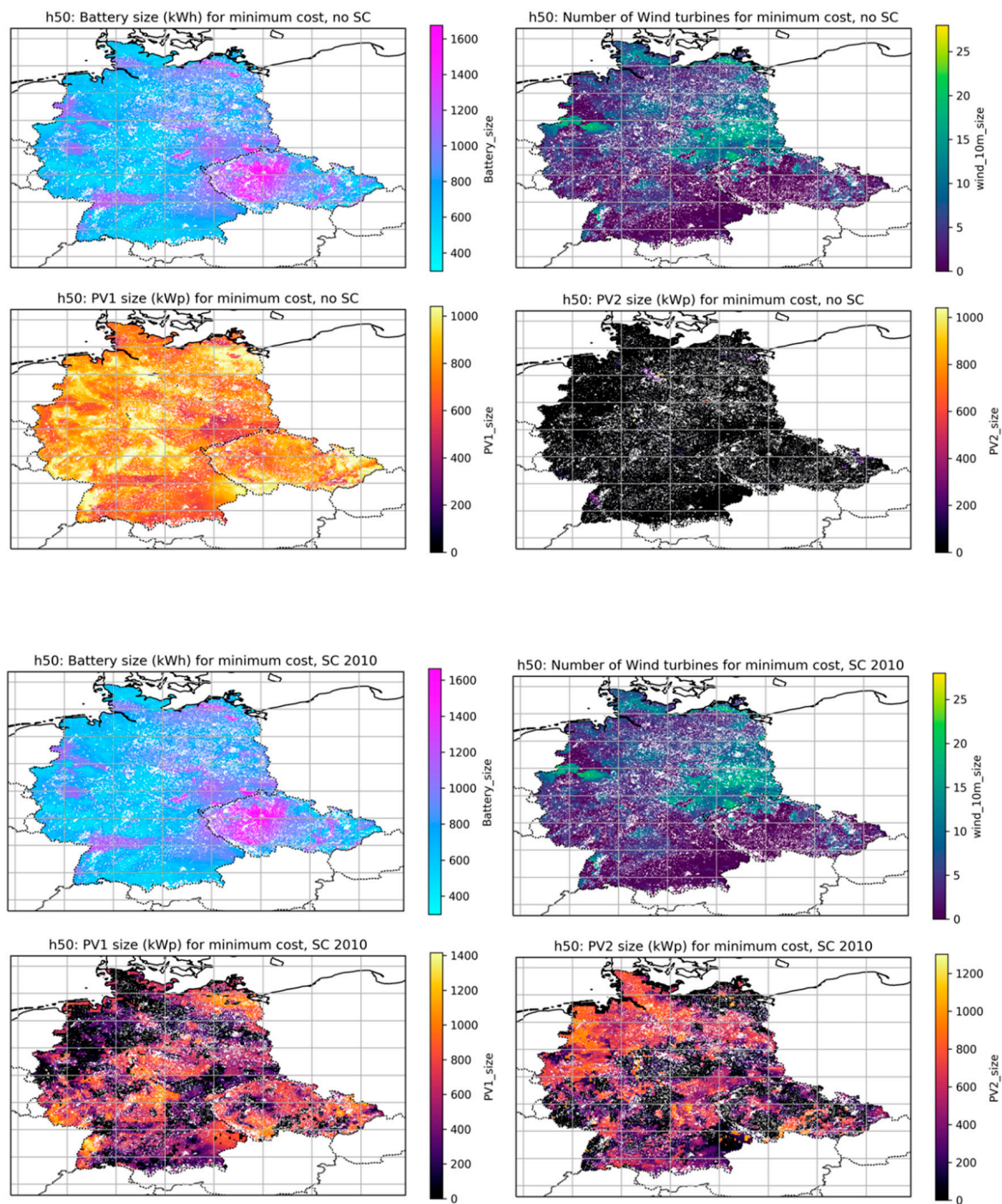


Figure 2. The main scenario for minimizing system costs without considering snow cover (top) and with snow cover (bottom) for clusters of 50 SFHs.

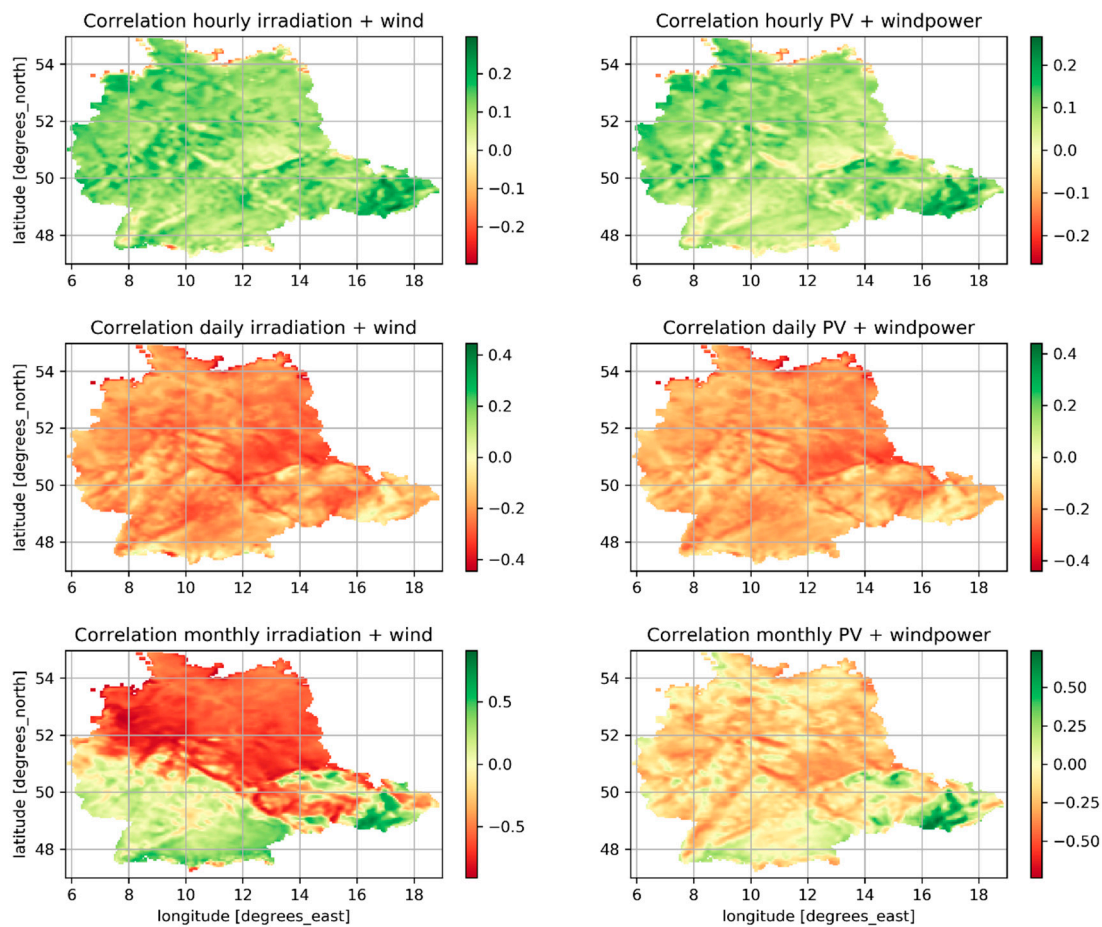


Figure 3. Complementarity between wind and solar resources (left column), as well as wind power and PV generation (right column) on hourly (top), daily (middle) and monthly (bottom) scale. High complementarity can be found in red areas whereas green areas indicate low complementarity.

A previous analysis using the same input data sets was conducted in [30], where electricity self-sufficiency was calculated for PV-battery systems only. Comparing scenario S7 and S16 from [30] a trend in PV size installations differing according to the latitude (the higher the latitude the more PV modules are required) can be identified. This trend is not continued in the present study. Even though wind energy seems to be a secondary generation source, it is able to compensate decreases in PV generation capacities in several regions and should therefore not be neglected. The storage capacity of the system depends on only a few days per year, mostly during winter with less sunshine and when relatively long periods of cloudy weather greatly reduce the production potentials of the PV system. In order to show the influence of wind turbines and the complementarities of the two technologies, additional to Figures 3–5 display a snapshot of a time series near Dresden. Figure 4 includes only the PV-battery system as simulated in [30] and Figure 5 concentrates on the presented hybrid PV-wind-battery system. For this particular location, it can be observed that the upgrade with optional wind power turbines significantly reduces the required battery storage sizes. Periods of little or no PV generation can be bridged much more effectively than in Figure 4, which we can see particularly in November of the modeled year. In both cases, the battery is used extensively, reaching its maximum SOC in mid-November and beginning of December in the PV-battery system and mid-November and end of December in the hybrid PV-wind-battery system. Comparing the two figures shows that the mix between wind and PV can considerably reduce battery storage requirements by almost half.

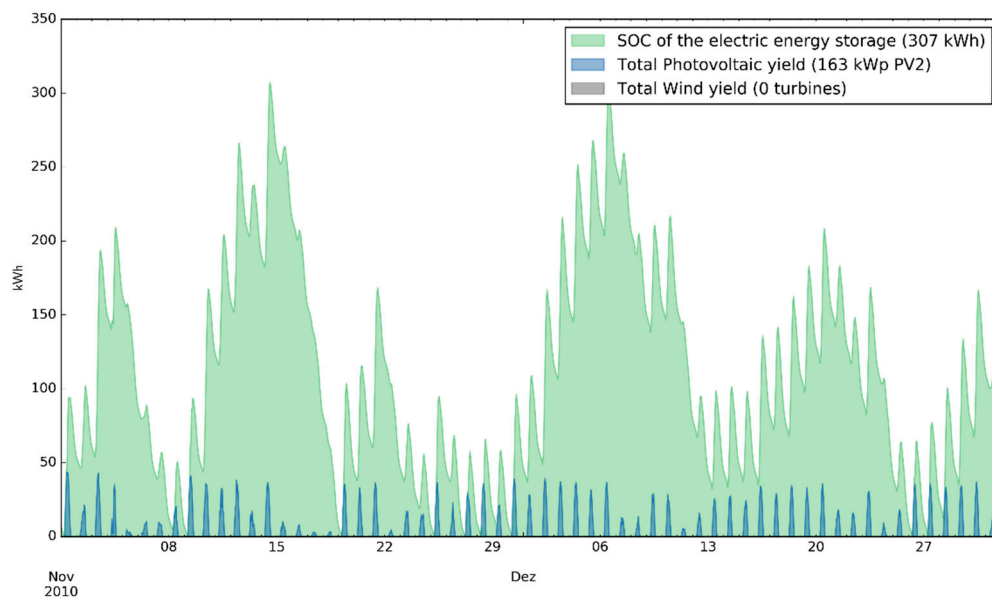


Figure 4. Time series of $eSOC_t$ of the battery and total PV output in a PV/battery system for clusters of 10 SFHs for November and December 2010 for a single pixel close to Dresden, Germany.

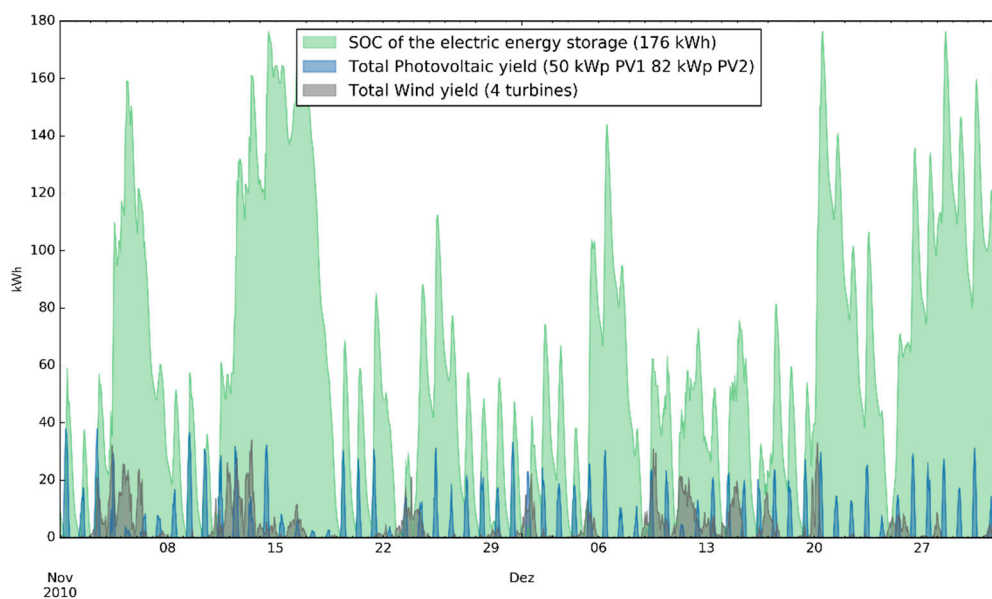


Figure 5. Time series of $eSOC_t$ of the battery, total PV output and total wind power output in a PV/wind/battery hybrid system for clusters of 10 SFHs for November and December 2010 for a single pixel close to Dresden, Germany.

Looking at the total costs of hybrid renewable electricity systems for clusters of 50 SFHs during a system's lifetime of 20 years, large regional deviations as shown in Figure 6 can be identified. The difference in total costs ranges by the factor of 2.8 comparing the cheapest and most expensive locations. A first look at the map shows that in general, Germany presents a higher advantage when combining PV and wind compared to the Czech Republic. The differences in total costs as well as in the spatial distribution of the results (across both countries) are very similar between the observed scenarios (with and without snow cover). Generally, the most unfavorable locations regarding investment costs are around the region of Prague, close to Dresden in the eastern part of Germany, as well as the regions near Freiburg and North Rhine-Westphalia. The highest total costs are to be found in these regions not only because of the low availability of resources but also due to their low complementarity (Figure 3).

In unfavorable regions, the maximum costs for 50 SFHs considering a total system life time of 20 years in the scenario considering snow cover, account for almost 5,000,000 €. Dividing the overall installation costs by the number of beneficiary households (50) and the number of months (in a given lifetime of 20 years, thus 240 months), provides an idea of the nominal costs per household and month. This simple calculation results in costs of around 425 € per household and month for a shared hybrid renewable electricity system not accounting for costs of financing or inflation. Regarding the most favorable regions (south of Germany), the monthly costs account for 175 € per household.

A brief comparison can be performed considering households with the same demands as assumed in the model and with current average national price per kWh -including taxes and levies - for medium sized households in Germany (0.295 € per kWh) and the Czech Republic (0.1573 € per kWh) [53]. The costs for the unfavorable regions are 5.6 times the current electricity expenditures of such residential users in Germany and 2.3 times for the regions with the lowest total costs. In the Czech Republic the differences are even higher with costs of 10.5 and 4.3 times higher for the unfavorable and favorable regions respectively. A total cost reduction by 340,000 € can be observed when snow cover is excluded compared to the scenario including the influence of snow cover. Thus, this impact reduces the costs of 175 € by 28 € per month and household. This opens a question about the value for homeowners of having a loss of power supply probability of Zero. If the owners of self-sufficient systems would accept, e.g., during long periods of low resources availability (such as long periods of snow coverage), a lack of enough electricity for full self-sufficiency, the total system cost could be considerable reduced.

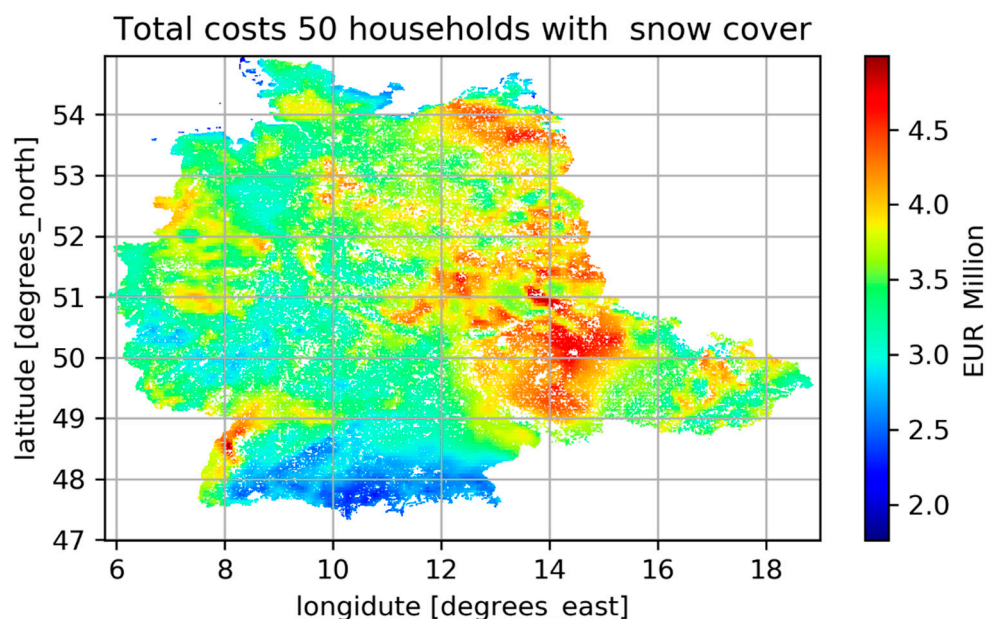


Figure 6. Total cost of hybrid renewable electricity systems for clusters of 50 residential buildings in the scenario considering snow cover.

4. Conclusions

In the presented study, the economically optimal configurations of PV-wind-battery systems are calculated with the help of a MILP model based on datasets of weather variables and population density as well as detailed technical specifications on the generation technologies. In the investigated low-populated regions of Germany and the Czech Republic, clusters of 10 and 50 Electricity Self-Sufficient Single Family Houses are modelled. The results show that including wind power in such self-sufficient systems decreases the comparatively high installed capacities of PV necessary at higher geographic latitudes due to lower solar irradiation while reducing total installation costs compared to PV-battery systems only. In areas of intermediate and high wind resources, storage capacities can be

significantly reduced. The results remain stable, even if limited PV production due to snow coverage is considered in the model.

Regarding particular areas, maps revealing the total costs for a hybrid renewable electricity system show most profitable locations in the south of Germany, as well as challenging locations mainly in the western part of the Czech Republic and in the eastern parts of Germany. There are important differences depending on weather conditions. In the majority of Bavaria in south Germany, as well as large areas in the western Czech Republic, small-scale wind power plants are not considered in a cost-minimized solution due to low wind resources and a lack of complementarity between wind and solar power. Total costs of the hybrid systems for the 50 households' clusters, aiming for full electricity self-sufficiency and without considering financing costs, range between EUR 1.8 million and EUR 5 million. These costs divided by the number of households and the amount of electricity that these would require in a 20 years' horizon are at least 2.3 (best locations in Germany) and up to 10.5 (worst locations in the Czech Republic) times larger than the current costs of obtaining electricity from the grid.

The results are not only relevant for groups of homeowners who consider installing a hybrid stand-alone renewable electricity system as a community, but also for investors or policy makers, as they present a guideline on how to size such systems and where in Germany and the Czech Republic, they are the most attractive regarding installation costs. Further research should focus on simulations with differing load profiles and under different policy and cost scenarios. Several cases of homeowners who reflect different levels of risk aversion with regards to levels of self-sufficiency, respectively the probability of loss of power supply and grid-dependency could further provide valuable insights. Such results may allow defining how technology improvements and cost reductions can impact the overall systems' profitability under regionally more explicit consumer behaviour scenarios. Finally, in order to assess full energy self-sufficiency, the study conducted here has to be extended to include the energy demand for heating/cooling of the households and alternative hybrid system configurations to supply it.

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