energies

MDPI

Article

Optimized Dimensioning and Economic Assessment of Decentralized Hybrid Small Wind and Photovoltaic Power Systems for Residential Buildings

Marcus Brennenstuhl [1], Robert Otto [2], Dirk Pietruschka [3,*], Björn Schembera [4] and Ursula Eicker [5]

[1] Enisyst GmbH, Robert-Bosch-Straße 8/1, 72124 Pliezhausen, Germany; marcus.brennenstuhl@enisyst.de
[2] Center for Sustainable Energy Technology, University of Applied Sciences Stuttgart, Schellingstraße 24, 70174 Stuttgart, Germany; robert.otto@hft-stuttgart.de
[3] NETZ: Technologietransferzentrum Nachhaltige Energien, Aschaffenburg UAS, Würzburger Str. 45, 63743 Aschaffenburg, Germany
[4] Institute of Applied Analysis and Numerical Simulation (IANS), University of Stuttgart, Allmandring 5b, 70569 Stuttgart, Germany; bjoern.schembera@mathematik.uni-stuttgart.de
[5] Next-Generation Cities Institute, Concordia University, 2155 Rue Guy, ER-1431.35, Montréal, QC H3H 2L9, Canada; ursula.eicker@concordia.ca
* Correspondence: dirk.pietruschka@th-ab.de

Abstract: In Germany, wind and photovoltaic (PV) systems dominate renewable electricity generation, with large wind turbines contributing 24.1% and PV systems contributing 10.6% in 2022. In contrast, electricity production from small wind turbines remains marginal (<0.01%). While currently only viable in high-wind locations, factors like rising electricity prices, cheaper battery storage, and increasing electrification could boost their future role. Within this work, a residential energy supply system consisting of a small wind turbine, PV system, heat pump, battery storage, and electric vehicle was dimensioned for different sites in Germany and Canada based on detailed simulation models and genetic algorithms in order to analyze the effect of bidirectional charging on optimal system dimensions and economic feasibility. This was carried out for various electricity pricing conditions. The results indicate that, with electricity purchase costs above 0.42 EUR/kWh, combined with a 25% reduction in small wind turbine and battery storage investment expenses, economic viability could be significantly enhanced. This might expand the applicability of small wind power to diverse sites.

Keywords: small wind turbine; heat pump; genetic algorithm; hybrid residential power systems; optimized dimensioning; energy economics; residential energy systems

check for updates

Academic Editors: Michele Roccotelli, Evangelos Karfopoulos and Ioannis Karakitsios

Received: 26 February 2025
Revised: 27 March 2025
Accepted: 31 March 2025
Published: 3 April 2025

Citation: Brennenstuhl, M.; Otto, R.; Pietruschka, D.; Schembera, B.; Eicker, U. Optimized Dimensioning and Economic Assessment of Decentralized Hybrid Small Wind and Photovoltaic Power Systems for Residential Buildings. *Energies* **2025**, *18*, 1811. https://doi.org/10.3390/en18071811

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Sector coupling and load management are crucial elements for reaching climate neutrality. Today, in Germany, most of the renewable energy sources (RESs) are converted within the domain of the energy sector; thus, it becomes important for effective load management to include an evergrowing share of volatile renewable energy (RE). At present, over 50% of this RE supply is derived from large wind turbines [1], characterized by their megawatt-level power output, which feeds into the medium- or high-voltage grid. Complementary to this, a significant portion of RESs is contributed by smaller decentralized plants, often feeding into the low-voltage grid, an arrangement that ideally encourages consumption within the same distribution grid. These are mainly photovoltaic (PV) and biogas plants that exemplify how an RE approach can be realized economically on a substantial scale. In Germany, this progress has been considerably driven by the deployment

of fixed feed-in tariffs over the past two decades, fostering the necessary economies of scale for financially feasible electricity production. In contrast, the adoption of small wind power plants has been notably limited in Germany. This is illustrated by the fact that electricity generation from small wind turbines constitutes less than 0.01% of the overall electricity output [2,3]. In comparison, the contribution of PV installations reached 10.6% in 2022, while large wind turbines accounted for 24.1% [1]. Typically, these systems are implemented separately in distinct technical and spatial contexts. Thus, the potential for localized integration between PV and wind power systems has received limited attention. This is unfortunate as cost-saving opportunities exist, particularly for small-scale installations, where shared fixed installation costs could be advantageous [4]. Also, due to their different generation profiles, wind power and PV have shown to complement each other [5,6].

Regarding small wind power, several factors underpin this discrepancy, including challenges in locating suitable sites, navigating complex legal frameworks, and the relatively modest subsidies available. The fact that the market for small wind systems is fragmented, which results in higher costs, alongside a lack of confidence in the technology, also contributes to the subdued presence of small wind power plants. This is unfortunate as the decentralized nature of small wind power at low-voltage grid level offers benefits like reducing the need for grid expansion or infrastructure upgrades. Although small wind power currently suits locations with favorable wind potential, changing factors such as rising electricity prices, falling battery storage costs, and growing electrification in heating [7] and transport [8] could create new opportunities.

1.1. Hybrid Power Generation from Small Wind Turbines and PV Systems

With regard to the combined operation of small wind turbines, PV systems and energy storage (battery as well as chemical storage), research so far has focused on the optimization of hybrid power generation [9] as well as optimized microgrid operation [10,11]. Sichilalu et al. [12] study a system with a grid-connected PV module, small wind turbine, and fuel cell in South Africa, but do not consider the thermal behavior of the building. In the study by Kaabeche et al. [13], an optimization model is developed for a hybrid system of a PV module, small wind turbine, and battery storage that models power-to-heat using electrical load profiles. Arabali et al. [14] analyze a heating, ventilation, air conditioning, and refrigeration (HVACR) system combined with a PV module and small wind turbine as well as electricity storage. System sizing as well as intelligent load management strategies are optimized using a genetic algorithm (GA). Thermal storage and thermal building dynamics are not considered.

Only a third of the publications refer to systems with a grid connection. At only 9.9%, sector coupling based on heat pump applications was very rarely investigated for this particular system combination [15]. Most publications do not reflect the dynamic behavior of the building, which means that an increase in flexibility due to overheating or undercooling and the associated rebound effect are not considered. Furthermore, there are few studies that explicitly refer to Germany as a location and the corresponding framework conditions. For example, of 550 studies published between 1995 and 2020 on the topic of small wind power in combination with a PV system, only three were examined with reference to Germany (one stand-alone system and two systems with grid connection) [15]. The basic approach of those studies by Grieser et al. [16], Rieck et al. [17] and Weida et al. [18] is comparable to the analyses presented within this work. Rieck et al. [17] examine the economic viability of small wind turbines for various locations in Germany in conjunction with PV systems and heat pumps in residential buildings. However, no future economic framework conditions are considered here. At the same time, the mutual influence of the self-consumption of electricity from PV

systems and small wind turbines is not addressed. Weida et al. [18] examine the interaction of PV systems and wind power plants for various regions in Germany but only refer to large wind power plants. Grieser et al. [16] examine the economic viability of small wind turbines for six urban locations in Germany. However, no integration of PV systems is considered.

1.2. Optimized Dimensioning of HVAC Systems

In research, metaheuristic optimization approaches, such as evolutionary algorithms (EAs) and, in particular, GAs, are often used to dimension the individual components in hybrid RE power supply systems. One reason for this is that such systems are often only dimensioned on the basis of empirical values, which are not or only insufficiently available in the case of changing framework conditions or new system combinations [19]. Specifically for hybrid systems, research has investigated the application of GAs for a wide variety of use cases. For example, Mayer et al. [20] use a GA to optimize a hybrid power system consisting of a PV module, small wind turbine, solar thermal collector, thermal buffer storage, and battery storage. In addition, thermal insulation thickness and life cycle impacts are included in the optimization. The optimization objective here is multi-criteria and relates to the full cost and environmental impact in terms of CO_2 emissions. Ko et al. [21] determine the optimal dimensioning of a system consisting of a PV module, solar thermal collector, heat pump, boiler, and chiller for an elementary school building using a GA in terms of life cycle cost, RE fraction, and CO_2 emissions caused. Koutroulis et al. [22] use a GA to find the optimal dimensioning of a photovoltaic module and small wind turbine to supply a household. Zhang et al. [23] apply a GA to a residential PV module, battery storage, and hydrogen storage system to increase self-sufficiency and reduce investment costs. Only the electrical side of the system, and not the thermal side, is considered. Bee et al. [24] use a GA to determine the optimal dimensioning of a system consisting of a heat pump, PV module, thermal buffer storage, and battery storage. Bernal-Agustin et al. [25] determine the optimal parameters for an EA to dimension a complex system of a PV module, small wind turbine, diesel generator, electrolyzer, fuel cell, and battery storage. Xu et al. [26] dimension a system of wind power, a PV module, and pumped storage using a GA, particle swarm optimization (PSO) and simulated annealing (SA). It is shown that, for this specific use case, PSO gives better results than the GA and SA.

1.3. Aim of This Work

The dimensioning of power systems is usually rule-based for cost reasons. In many cases, however, this is not the most optimal solution, since the building, user-specific, and climatic conditions vary, which can only be represented in part by a rule-based dimensioning. Another problem is that the rule-based dimensioning loses its validity when the general conditions change (investment and energy costs or yields, possible subsidies, and efficiency of the systems), or when new rules have to be created, for which empirical values are first required. In addition, there is hardly any practical experience for the combination of PV systems and small wind turbines.

Therefore, within this work, a dimensioning of a residential building's individual energy system components (small wind turbine, PV module, battery storage, heat pump, thermal buffer storage) was carried out by means of a metaheuristic (i.e., a genetic) optimization algorithm. The optimization goal is based on the economic efficiency in the form of the equivalent annual costs for different locations. Current and various future scenarios were examined with regard to the varying economic conditions, such as investment costs, electricity purchase prices, and electricity marketing prices. In addition, the effect of integrating battery electric vehicles (BEVs) by means of bidirectional charging (vehicle-to-home) on the

economic efficiency of the PV system and the small wind turbine unit was evaluated for the 2022 scenario.

It was observed that higher electricity procurement costs (≥0.42 EUR/kWh), coupled with a 25% reduction in investment expenditures for small wind turbines and battery storage, could significantly enhance the economic viability of small wind turbines for residential buildings equipped with heat pumps. Under these circumstances, small wind turbines would become attractive for a broader array of additional locations. In most cases, the current feed-in tariff or direct marketing at exchange electricity prices ≥ 60 EUR/MWh would prove sufficient for an economically viable operation.

Simultaneously, concerning the intensifying electrification of the transportation sector and the prospects of bidirectional charging, it was demonstrated that, within existing conditions, the integration of BEVs and bidirectional charging does not positively influence the economic feasibility of the considered scenarios for small wind turbine installations. Nonetheless, under future conditions, the load management of heat pumps or BEV charging could potentially exert a positive impact on the profitability of small wind turbines.

2. Methodology

2.1. Boundary Conditions

This study is based on a residential building located within a plus-energy settlement situated in the German municipality of Wüstenrot. It includes a heat pump fed by a cold district heating grid that operates at lower temperatures, supplemented by two thermal buffer storage tanks and a PV system. The specific building parameters are shown in Figure 1. Additionally, over the span of multiple years, detailed measurements of all relevant energy flows were gathered in high resolution.

Building upon this dataset, a detailed white-box model was created within the INSEL simulation environment. This model was calibrated based on the collected empirical data and subsequently validated. This calibration and validation approach is described in detail in [27,28]. For a more in-depth understanding of the configuration of the local cold district heating grid and the plus-energy settlement, additional insights can be found in [29].

Building ID	**12**
Heat pump	Waterkotte Modell DS 5023.5Ai, 22.2 kW
Thermal buffer storage	DHW 400l; Heating 1000l
Battery storage	None
Installed PV power	13.64 kWp
PV orientation	58.4 m² (48 mod.) orientation 180°, tilt 15°; 49.5 m² (40 mod.) orientation 0°, tilt 15°
PV manufacturer and model	Solar Frontier Typ SF155-L
Residential useable area	285.13 m²
Heating demand	22,696 kWh

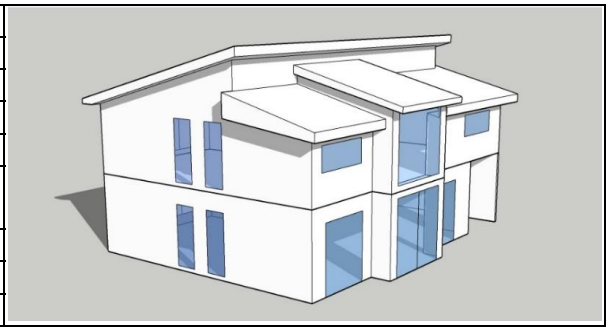


Figure 1. Building system specifications. The heat pump was manufactured by Waterkotte GmbH, 44628 Herne, Germany. The PV system was manufactured by Solar Frontier K.K., Tokyo 108-6209, Japan.

A metaheuristic optimization was chosen due to the model being run as a co-simulation, with the optimization being realized in Python 3.10 and the building and energy supply model in INSEL. This was carried out because INSEL achieves more detailed results of the energy supply system compared to common solutions in Python, like OemOf [30]. The control variables of the optimization were thermal heat pump power rating (15–25 kW), DHW and space heating buffer storage sizes (500–3000 L), battery storage capacity (0–20 kWh), PV peak power (0–20 kWp), and rated wind turbine power (0–20 kW)

in 1 kW or 100 l steps. The optimizations were carried out for a time span of an entire year with a time resolution of one minute for each pilot site.

With this validated digital twin, different locations in Germany and abroad were investigated, based on measured data of wind speed, global radiation, ambient temperature, and ground or brine temperature. An overview of the general conditions of the different investigated locations is given in Table 1. For the brine-side flow temperature of the heat pump, the same annual profile measured in Wüstenrot was used for the sites in Germany. For the Montreal site, a separate profile based on the mean brine temperatures for the ground-source heat pump operation in Montreal [31] was used.

Montreal was chosen due to its good data availability and its research-cooperative ties that could potentially provide a basis for future research based on this methodology, especially as Canada is a country with a high domestic heating demand and, so far, has a low utilization rate of heat pumps, especially when taking into account that 35% of the heat supply was carried out by direct electrical heating in 2021 [32].

When examining Table 2, it becomes apparent that the average annual wind speed at the locations ranges between 1.5 m/s and 5.1 m/s over a ten-year average. This aligns with a geospatial analysis of wind data derived from [33], which indicates that over 58% of potential locations in Germany fall within this range. The average annual temperature of the locations is between 7.2 °C and 10.6 °C, which, according to DIN EN 12831 [34], corresponds to 59% of locations in Germany. The Montreal site serves as a comparative case with German data. It represents an urban environment within the Canadian climate zone Dfb (Humid Continental Mild Summer, Wet All Year) [35]. However, to draw further conclusions for Canada, additional simulations for other locations in different climate zones would be necessary.

Table 1. Studied sites. Data sources: (a) [36]; (b) [37]; (c) [38]; (d) [31].

Location	Data Resolution	Data Source	Measurement Height [m]	Hub Height [m]	Roughness Exponent [-]
Aachen	10 min	DWD [(a)]	5	10	0.16
Braunlage	10 min	DWD [(a)]	8	15	0.28
Greifswald	10 min	DWD [(a)]	5	10	0.28
Potsdam	10 min	DWD [(a)]	18	15	0.28
Stuttgart	30 min	CFD simulation [(b)]	30	30	no scaling
Wüstenrot	1 h	Own measurements	5	15	0.28
Montreal	1 h	ECCC [(c,d)]	20	20	no scaling

The weather data on which the simulations are based (wind speed, global radiation, and ambient temperature) represent the year 2019. Looking at Table 2, it can be seen that, for the year 2019, the mean values deviate only slightly from the 10-year average. For the Wüstenrot and Stuttgart sites, insufficient historical data were available for comparison. The measured average wind speeds range between 1.5 m/s at the Stuttgart site and 5.1 m/s at the Aachen site. It should be mentioned that, under the current framework conditions, an average annual wind speed of 4.0 m/s and above can be assumed to be sufficient for the economic operation of small wind turbines [39].

Table 2. Average measured annual values of the sites.

	$\overline{V}_{wind}$ 2019 [m/s]	$\overline{V}_{wind}$ 2010–2020 [m/s]	$\overline{\Theta}_{amb}$ 2019 [°C]	$\overline{\Theta}_{amb}$ 2010–2020 [°C]	$\overline{G}_{oh}$ 2019 [W/m^2]	$\overline{G}_{oh}$ 2010–2020 [W/m^2]
Aachen	5.1	5.1	10.9	10.6	125.1	121.5
Braunlage	3.6	3.4	8.1	7.2	115.1	112.0
Greifswald	4.1	4.2	10.5	9.5	122.6	119.2
Potsdam	4.0	4.0	11.3	10.2	130.1	124.5
Stuttgart	1.5	-	12.8	-	124.8	-
Wüstenrot	2.3	-	9.2	-	126.2	-
Montreal	4.6	4.5	6.9	7.8	149.7	134.2

2.2. Overall System Cost Function

The objective function of the optimization is based on a dynamic economic evaluation using the annuity method according to VDI 2067 Wirtschaftlichkeit gebäudetechnischer Anlagen [40]. The economic evaluation is calculated in the form of the equivalent annual cost (EAC). This consists of the annual expenditures for the investment, operation, and maintenance of the various system components. The EAC is calculated according to the following Equation (1):

$$f_{EAC} = f_{Hardware} + f_{Energy} \tag{1}$$

Here, $f_{Hardware}$ is calculated by the following Equation (2):

$$f_{Hardware} = \sum_i P_i + \sum_i OM_i \tag{2}$$

OM_i [€] is the sum of the annual fixed and variable operating and maintenance costs of the specific system component i (usually a percentage of P_i). P_i [€] is the annualized capital cost of the investment for the specific system component i, calculated according to the following Equation (3):

$$P = PV \cdot \frac{r_i}{1 - (1 + r_i)^{-n_{Life}}} \tag{3}$$

where PV [€] is the present value of the total investment, including possible subsidies, r_i [%] is the annual interest rate, and n_{Life} [years] is the estimated lifetime of the investment. The energy cost of this system (see Equation (4)) consists of the amount of electricity $Q_{i,in}$ [kWh] purchased from the grid and the amount of electricity $Q_{i,out}$ [kWh] fed into the grid, in conjunction with the respective specific prices. For the fed-in electricity, a distinction is made here between different feed-in tariffs for the PV system and small wind turbine. For the total electricity costs, the sum of the electricity grid purchase with a purchase price of $c_{i,in}$ [€/kWh] and the sum of the electricity fed in with a feed-in tariff of $c_{i,out}$ [€/kWh] are considered.

$$f_{Energy} = \sum_i Q_{i,in} \cdot c_{i,in} - \sum_i Q_{i,out} \cdot c_{i,out} \tag{4}$$

2.3. Investment Costs

The calculated investment costs of the different energy supply systems depending on their dimensioning and the maintenance costs, as well as the assumed lifetime, are presented in the Appendix A in Table A1.

Figure 2 shows the linear interpolation of investment costs over the individual system variables considered in the optimization. The investment costs include the installation costs. Subsidies are not taken into account since there are significant regional differences, e.g.,

for battery storages. The power output or demand of the heat pump and the PV system is scaled linearly. For the small wind turbine, the characteristic curves published by the manufacturer were used for turbines of the types Aeolos-V 1 kW, Aeolos-V 3 KW, Aeolos-V 5 kW, and Aeolos-V 10 kW. Between these sizes, the characteristic curves were interpolated. This is shown in Figure 3.

For all variants, the interest rate is set to 3%. A monthly connection fee of EUR 7 per installed kW of thermal heat pump capacity is assumed for the connection to the cold district heating network. The feed-in tariff for the PV system is assumed to be 0.0653 EUR/kWh for a size up to 10 kWP, and 0.0634 EUR/kWh for a size between 10 kWp and 30 kWp, which corresponds to the subsidy rates in Germany as of April 2022.

The feed-in tariff for the small wind turbine is assumed to be 0.0618 EUR/kWh and the electricity purchase price is assumed to be 0.34 EUR/kWh. This also corresponds to the costs in April 2022. In the course of 2022, the electricity purchase prices have increased, in some cases significantly, by up to 70%. However, this situation appears to be easing and, according to [41], household prices for new customers are now back to an average of 0.32 EUR/kWh, whereas, for existing customers, they are 0.44 EUR/kWh with a downward trend.

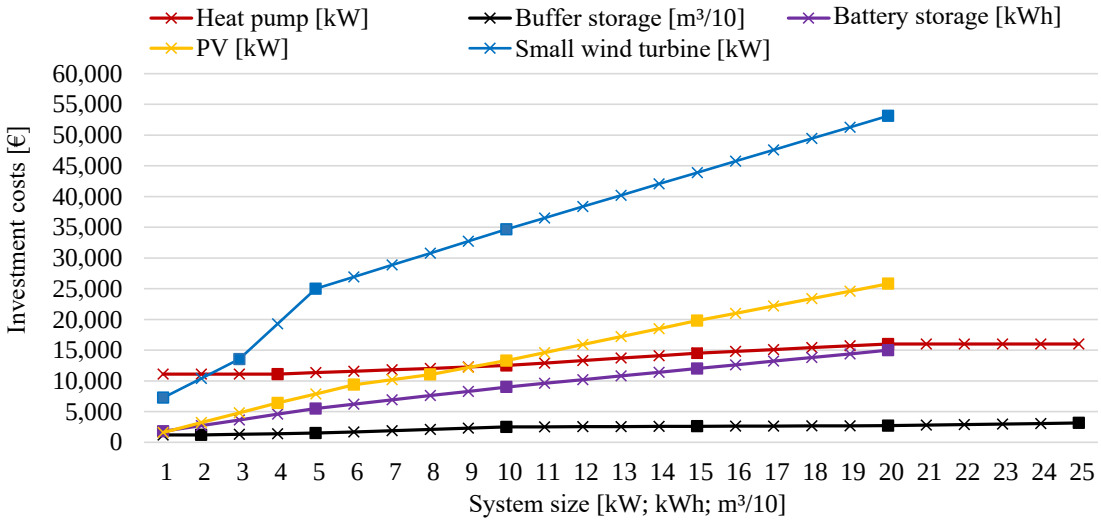


Figure 2. Interpolated investment costs depending on the system size of the considered system components.

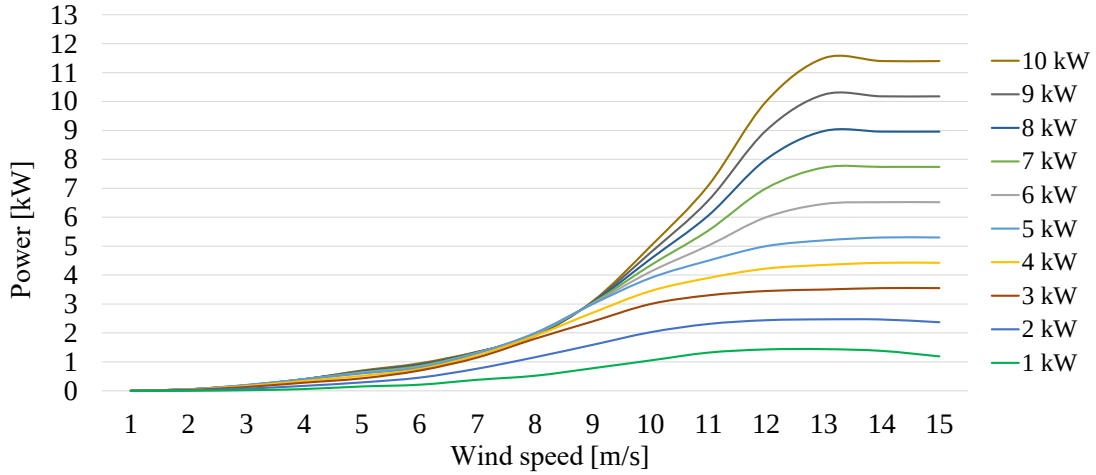


Figure 3. Interpolated power curves depending on the wind speed of the considered small wind turbines' power rating.

3. Results

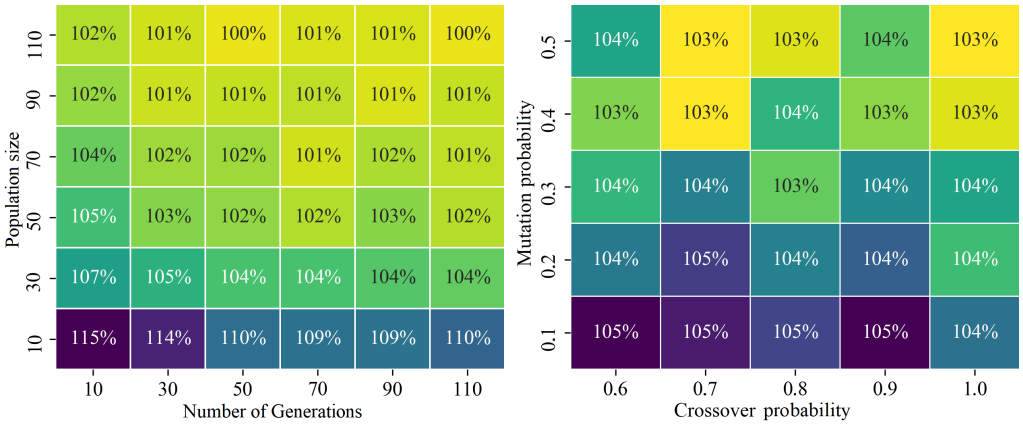
3.1. Optimal Parameters for Genetic Algorithms

To identify optimal parameters for the utilized genetic algorithm application, aiming to find the right balance between computational efficiency and proximity to a global optimum, an iterative study was carried out as outlined in [19]. This involved an incremental iteration in which the number of generations and the population size were adjusted in increments of 20, ranging from 10 to 110. Simultaneously, the crossover probability was iterated in intervals of 0.1, spanning from $p_c = 0.6$ to $p_c = 1.0$. Additionally, the mutation probability underwent incremental changes in steps of 0.1, ranging from $p_m = 0.1$ to $p_m = 0.5$. The selection of these parameter bounds for the crossover probability is grounded in their established prevalence within the literature [42,43]. As for the mutation probability limits, these were determined empirically. To mitigate result variances, which are particularly noticeable when dealing with a low number of generations or a small population size, each parameter combination underwent three separate computations.

The culmination of these varied parameter combinations is visually depicted in Figure 4a,b. The percentage values associated with these figures denote the increase in costs, serving as a gauge of deterioration relative to the most optimal outcome.

It can be seen in Figure 4a that population size has a stronger influence than the number of generations. The overall relatively small deterioration of up to 115% can be attributed to the fact that this value represents the average of the different iterated crossover and mutation probabilities. Thus, it includes all good and bad combinations. Looking at the results of the varied population size and number of generations in Figure 4a, we see a balance between computation time and result quality for a population size of 90 combined with a number of 30 generations. Looking at the results of varying crossover and mutation probabilities in Figure 4b, the best results are obtained in conjunction with a crossover probability of $0.7 \leq p_c \leq 1.0$ and with a mutation probability of $0.4 \leq p_m \leq 0.5$. Based on this, the following parameters are considered optimal for the present use case of optimized dimensioning [19].

- Number of generations: 30;
- Population size: 90;
- Two-point crossover; crossover probability: 1.0;
- Uniform mutation; mutation probability: 0.5;
- Competition selection; tournament size: 5.



(**a**) Dependence of mutation and crossover probabilities. Mean value over all numbers of generations and population sizes.

(**b**) Dependence on population size and number of generations. Mean value over all mutation and crossover probabilities.

Figure 4. Parameter0 variation of a genetic algorithm for optimized dimensioning. Own representation, already published in [19].

3.2. Current Framework Conditions

To provide a starting point for comparison, optimized dimensioning of the components is first performed for all sites based on current conditions in terms of electricity purchase prices, electricity marketing prices, and investment costs. This is shown in Table 3.

Table 3. Optimized dimensioning and economic efficiency of the energy supply system for different locations, current conditions (energy and investment costs as of 2022).

Location	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	Total Costs [EUR/a]	Energy Costs [EUR/a]	Invest. and Maintenance [EUR/a]
Aachen	15	0.5	0.7	1	4	3	7084	1925	5159
Braunlage	15	0.5	0.8	0	9	0	7922	3732	4190
Greifswald	15	0.5	0.6	0	4	0	7430	3799	3631
Potsdam	15	0.7	0.6	0	5	0	7428	3625	3803
Stuttgart	15	0.6	0.5	0	8	0	6868	2819	4049
Wüstenrot	15	0.6	0.6	0	8	0	7541	3472	4069
Montreal	15	0.7	0.6	2	9	3	8316	2517	5798

This shows that small wind turbines can only be operated economically in the locations with high wind potential, Aachen and Montreal. The same is true for battery storage, which, despite an installed PV system and heat pump operation, would only be economical in the case of an additional small wind turbine and, even then, only at a very small size (1–2 kWh). The size of the heating buffer storage is moderate at 0.5–0.8 m^3. The PV system is sized to between 4 and 9 kWp depending on the irradiance of the site.

3.3. Current Framework Conditions with Vehicle-to-Home

To investigate the impact of the ever-increasing number of BEVs and the associated storage potential in the context of a vehicle-to-home application, one BEV was added to each of the sites under the current framework conditions. The assumption here is that the applied 80 kWh vehicle battery will be used between a 40% and 60% of SOC, if possible, in order to ensure a high cycle stability of the battery. This means that the upper limit is 48 kWh, the lower limit is 32 kWh, and, thus, the usable capacity is 16 kWh. The efficiency for combined charging and discharging is assumed to be 80%. Furthermore, two different driving profiles are investigated, the first being commute to work, and the second being usage as a secondary car, which has longer parking hours at home at the charging port. These profiles are based on data from the German mobility atlas [44] and driving and demand profiles derived from [45]. Charging and discharging of the vehicle took place whenever they were available. Since no load management was implemented in this case, uncertainty regarding availability was not taken into account. The primary motivation for including this variant is to determine whether using the BEV's battery as temporary storage, without incurring additional investment costs, could improve the economic viability of small wind turbines.

The results for the first driving profile, which generally has an absence of the vehicle during the day on weekdays at times of greatest PV power production, are shown in Table 4. The results for the second driving profile, which has a greater presence of the vehicle and thus greater flexibility, are shown in Table 5.

It can be seen that, for the driving profile of the first car, commuting to work as shown in Table 4, the dimensioning of the PV system is the same size or partly smaller depending on the location compared to the dimensioning without the BEV as shown in Table 3. This

can be attributed, among other things, to the fact that the BEV is not available at times of highest PV power generation and that the efficiency for combined charging and discharging is lower compared to a fixed battery storage (80% vs. 90%). It should be noted here that the financial differences in the sizing of the individual components are sometimes quite close. For example, in the case of Wüstenrot, increasing the PV system to 8 kWp would only mean a difference of EUR 27 per year in the overall balance. The economic efficiency of a small wind turbine is not improved with this driving profile in connection with the assumed framework conditions. In the case of the Montreal site, it even gets worse. In the first-car, commute-to-work variant, the energy costs of the entire system (household electricity demand, heat pump, and BEV) remain roughly constant compared to the variant without the BEV, despite the additional purchase of 2410.7 kWh of electricity for the BEV, because vehicle-to-home use can increase electricity self-consumption without additional investment costs.

Table 4. Optimized dimensioning and economic efficiency of the energy supply system for different locations, actual state with vehicle-to-home (driving profile of first car, commuting to work, energy and investment costs as of 2022).

Location	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	Total Costs [EUR/a]	Energy Costs [EUR/a]	Invest. and Maintenance [EUR/a]
Aachen	15	0.5	0.5	16	0	3	7199	2847	4351
Braunlage	15	0.5	0.6	16	4	0	7912	4282	3631
Greifswald	15	0.5	0.5	16	4	0	7502	3891	3611
Potsdam	15	0.8	0.6	16	9	0	7490	3281	4210
Stuttgart	15	0.7	0.5	16	9	0	6995	2824	4171
Wüstenrot	15	0.6	0.5	16	4	0	7584	3953	3631
Montreal	15	0.7	0.7	16	10	0	8268	3957	4312

Table 5. Optimized dimensioning and economic efficiency of the energy supply system of a single building for different locations, actual state with vehicle-to-home (driving profile of second car, energy and investment costs as of 2022).

Location	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	Total Costs [EUR/a]	Energy Costs [EUR/a]	Invest. and Maintenance [EUR/a]
Aachen	16	0.5	0.5	16	8	3	6856	1395	5462
Braunlage	15	0.6	0.7	16	9	0	7700	3510	4190
Greifswald	15	0.7	0.5	16	10	0	7261	2989	4273
Potsdam	15	0.7	0.5	16	8	0	7152	3084	4069
Stuttgart	15	0.5	0.5	16	11	0	6556	2205	4351
Wüstenrot	15	0.7	0.6	16	10	0	7367	3075	4292
Montreal	15	0.6	0.6	16	12	0	7889	3382	4507

Regarding the second-car driving profile, it can be seen in Table 5 that, due to the higher availability of the BEV and the resulting greater flexibility, the dimensioning of the PV system is significantly larger. On average, a 49% larger PV system would make sense compared to the dimensioning without the BEV (see Table 3). At the same time, under the current conditions, there is no positive impact on the size of the small wind turbine, but this could be different under possible future scenarios. In the case of the Montreal site, as with the first-car, commute-to-work driving profile, it actually becomes worse, which

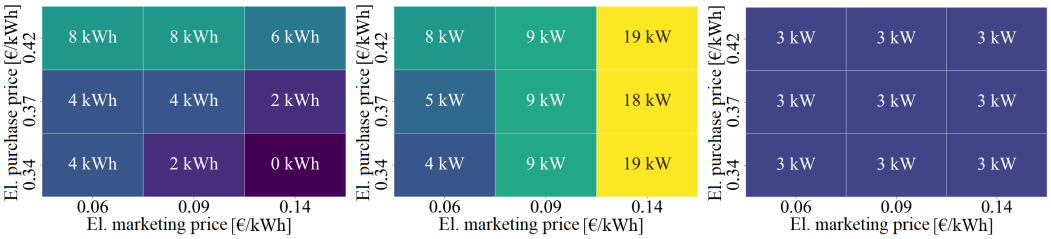
can be attributed to the lower availability and efficiency of the vehicle battery charging and discharging process compared to stationary battery storage. Due to the increased self-consumption, the electricity costs of the entire system even decrease noticeably in the variant second-car driving profile, despite the 1366.3 kWh increase in demand due to the BEV. However, these economic evaluations do not include any possible damage to the vehicle battery due to additional cycles. According to a study carried out previously, this would be between EUR 175.5 and EUR 271.6 per year, depending on the driving profile, whereby the number of cycles in the variants studied is higher than in the case studied here due to optimized charge load management. In this context, however, it must also be considered that bidirectional operation takes place in the range of an SOC between 40% and 60%, which means a high cycle stability and thus the vehicle's service life possibly being reached sooner despite vehicle-to-home operation, rather than the vehicle battery falling below 80% in capacity [46].

3.4. Future Framework Conditions

In the following, the system components are dimensioned for the different locations with respect to increasing electricity purchase and electricity marketing prices and decreasing capital costs. Thereby the system components are each dimensioned for various cost combinations. These are an electricity purchase price of 0.34 EUR/kWh, 0.37 EUR/kWh, and 0.42 EUR/kWh; an electricity marketing price of 0.06 EUR/kWh, 0.09 EUR/kWh, and 0.14 EUR/kWh; and an investment cost reduction of the battery storage and the small wind turbine by 25% and by 50%, respectively. The costs of the remaining system components (heat pump, PV system, and thermal buffer storage) remain constant with respect to the calculation time of the dimensioning, which would otherwise increase eightfold. This restriction is accepted since this work primarily focuses on the potential of small wind turbines and, also, research indicates that battery storage cost development will play a more important role compared to PV cost development in future scenarios, as the future adoption of PV and PV-T (thermal) systems is expected to depend heavily on advancements in energy storage technologies that are both efficient and economical [47]. Over the past 12 years, the total installation costs for large PV systems have declined significantly, with an average annual decrease of approximately 12%. However, the costs for non-module components such as inverters, mounting systems, switches, wiring, and installation work have remained relatively stable since 2014 [48]. Recent estimates place the unit investment costs for PV systems at around 870 USD/kWp, with projections indicating a drop to below 700 USD/kWp shortly after 2030 and further reductions to approximately 560 USD/kWp by 2050 [49]. In parallel, lithium-ion battery technology is expected to see substantial cost reductions. The cost of battery cells is anticipated to decrease by nearly 50% between 2023 and 2030, driven by advancements in production techniques and economies of scale [50].

3.5. Aachen, Germany

Figure 5a–c show the optimal battery storage, PV system, and small wind turbine sizes for the Aachen site for different electricity purchase and marketing prices, with an investment cost reduction of 25% for a small wind turbine and battery storage compared to today's prices. In Figure 6a–c, this is carried out for an investment cost reduction of 50%. Thereby, green and more yellow colors indicate that a large system is more economical. The detailed results showing the specific annual investment, maintenance, and energy costs, as well as the dimensioning of the additional system components (heat pump and heating and domestic hot water (DHW) buffer storage), are presented in the Appendix A in Table A2.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

Figure 5. Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 25% for small wind turbine and battery storage, Aachen site.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

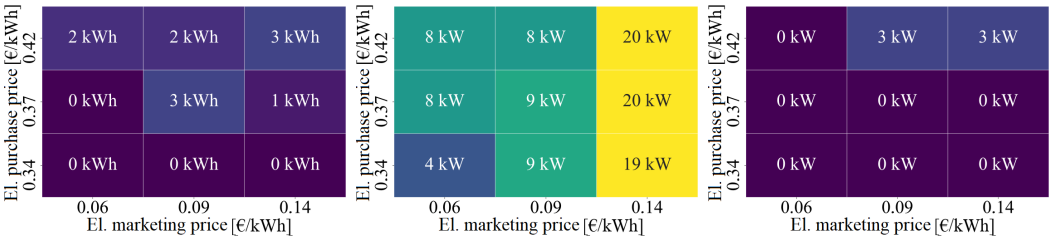
Figure 6. Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 50% for small wind turbine and battery storage, Aachen site.

It can be seen that the operation of a small wind turbine is economical for all constellations. However, this is already the case for this location under the current framework conditions. The optimal size is 3 kW. The battery storage size is equally influenced by the electricity purchase price and the electricity marketing price for a 25% investment cost reduction. In the most favorable case (electricity purchase price of 0.42 EUR/kWh; electricity marketing price of 0.06 EUR/kWh), a battery storage size of 8 kWh would be the most economical. In the worst case (electricity purchase price of 0.34 EUR/kWh; electricity marketing price of 0.14 EUR/kWh), the installation of a battery storage would not make sense. With a 50% investment cost reduction, it can be seen with regard to the battery storage that the storage sizes representing the best economic efficiency are significantly larger. Even in the worst case, a battery storage of 7 kWh would still be the most economical. The dimensioning of the PV system shows a relatively small influence of the battery storage size on the economic efficiency. The electricity purchase price has a moderate effect on the economic efficiency, while the electricity marketing price has a significant effect. In the most favorable case of an electricity marketing price of 0.14 EUR/kWh, a PV system size between 19 and 20 kWp would be the most economical. In the worst case (electricity purchase price of 0.34 EUR/kWh; electricity marketing price of 0.06 EUR/kWh), a PV system size of 4 kWp would be the most economical. The optimal heat pump size is 15 kW throughout, and the optimal buffer storage sizes vary between 0.5 m^3 and 0.9 m^3 for heating and DHW storage for all combination options.

3.6. Braunlage, Germany

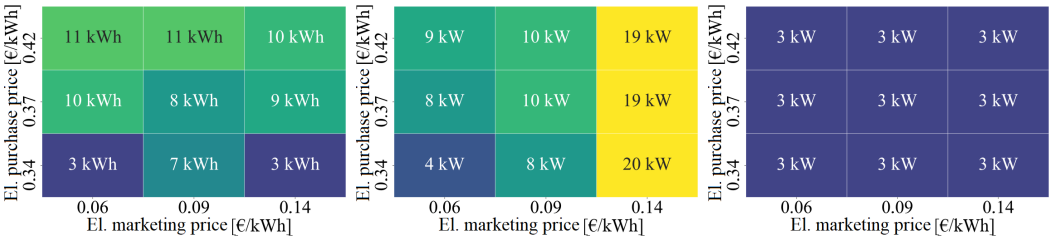
Figure 7a–c show the optimal battery storage, PV system, and small wind turbine sizes for the Braunlage site for different electricity purchase and marketing prices, with an investment cost reduction of 25% for a small wind turbine and battery storage compared to today's prices. In Figure 8a–c, this is carried out for an investment cost reduction of 50%. Thereby, green and more yellow colors indicate that a large system is more economical. The detailed results showing the specific annual investment, maintenance, and energy costs, as

well as the dimensioning of the additional system components (heat pump and heating and DHW buffer storage), are presented in the Appendix A in Table A3.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

Figure 7. Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 25% for small wind turbine and battery storage, Braunlage site.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

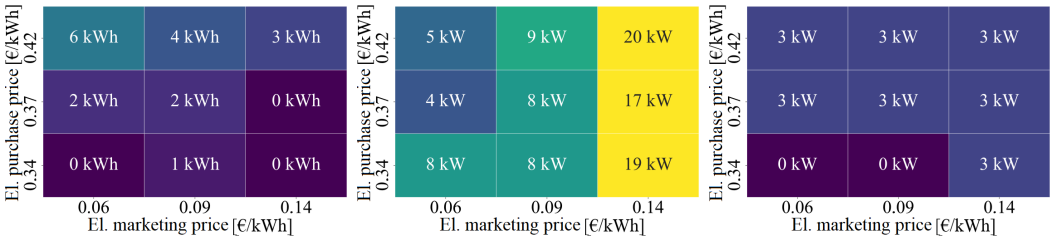
Figure 8. Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 50% for small wind turbine and battery storage, Braunlage site.

In the case of this site, the dimensioning shows clear differences with regard to the different investment costs for the battery storage and small wind turbine, which can be attributed to the lower yield of the small wind turbine. In the case of an investment cost reduction of 25%, a small wind turbine would thus only make sense at an electricity purchase price of 0.42 EUR/kWh and an electricity marketing price of 0.09 EUR/kWh or 0.14 EUR/kWh. For an investment cost reduction of 50%, the operation of a small wind turbine would make sense for all electricity purchases and electricity marketing price constellations. The best small wind turbine size would be 3 kW. The optimal battery storage size at a 25% investment cost reduction is influenced by the electricity production, the electricity purchase price, and the electricity marketing price. In the best case (3 kW small wind turbine; 20 kWp PV system; electricity purchase price of 0.42 EUR/kWh; electricity marketing price of 0.14 EUR/kWh), a battery storage size of 8 kWh would be the most economical. At an electricity purchase price of 0.34 EUR/kWh, a battery storage system does not make sense for all electricity marketing prices. With a 50% investment cost reduction, it can be seen with regard to the battery storage that it makes sense for all constellations. At an electricity purchase price of 0.34 EUR/kWh, storage sizes of 3–7 kWh would make sense, depending on the electricity marketing price and the size of the PV system. For an electricity purchase price of 0.42 EUR/kWh, which favors the use of a battery storage, the optimal storage size would be between 10 kWh and 11 kWh. Looking at the detailed results in Table A3, it can also be seen that, if the investment cost of the small wind turbine is reduced by 50% and that of the battery storage is reduced by 25%, the most economic small wind turbine size would be the same as for the variant of the investment cost reduction of the small wind turbine and battery storage by 50%. The small wind turbine investment cost has the greater impact here. The sizing of the PV system shows a relatively small influence of the battery storage size. The electricity purchase price has a moderate impact, while the electricity marketing price has a significant impact. In the most

favorable case of an electricity marketing price of 0.14 EUR/kWh, a PV system size between 19 and 20 kWp would be the most economical. In the worst case (electricity purchase price of 0.34 EUR/kWh; electricity marketing price of 0.06 EUR/kWh), a PV system size of 4 kWp would be the most economical. The optimal heat pump size is 15 kW throughout, and the optimal buffer storage sizes vary between 0.5 m^3 and 0.8 m^3 for heating and DHW storage for all combination options.

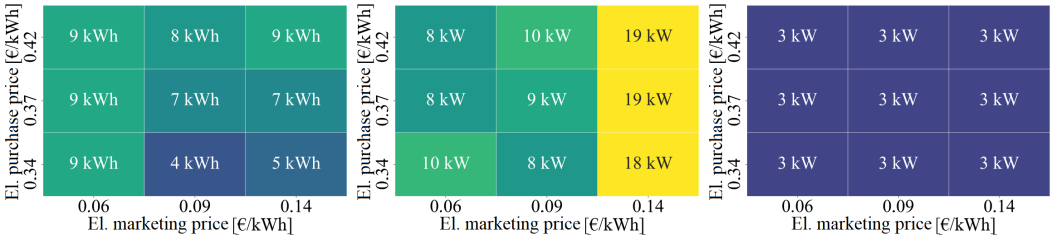
3.7. Greifswald, Germany

Figure 9a–c show the optimal battery storage, PV systems, and small wind turbine sizes for the Greifswald site for different electricity purchase and marketing prices, with an investment cost reduction of 25% for a small wind turbine and battery storage compared to today's prices. In Figure 10a–c, this is carried out for an investment cost reduction of 50%. Thereby, green and more yellow colors indicate that a large system is more economical. The detailed results showing the specific annual investment, maintenance, and energy costs, as well as the dimensioning of the additional system components (heat pump and heating and DHW buffer storage), are presented in the Appendix A in Table A4.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

Figure 9. Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 25% for small wind turbine and battery storage, Greifswald site.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

Figure 10. Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 50% for small wind turbine and battery storage, Greifswald site.

In the case of the Greifswald site, there are clear differences in the dimensioning depending on the investment cost reduction, especially for the battery storage size. Compared to the current situation in Table 3, a small wind turbine would make sense for all combination options with an investment cost reduction of 25%, except for an electricity purchase price of 0.34 EUR/kWh and an electricity marketing price of 0.06 EUR/kWh or 0.09 EUR/kWh. The best small wind turbine size here would be 3 kW. For an investment cost reduction of 50%, the operation of a small wind turbine would make sense for all electricity purchases and electricity marketing price constellations. The best small wind turbine size would also be 3 kW. The optimal battery storage size at a 25% investment cost reduction is influenced by the expected yield, the electricity purchase price, and the electricity marketing price. In the best case (3 kW small wind turbine; 5 kWp PV system; electricity purchase price of 0.42 EUR/kWh; electricity marketing price of 0.06 EUR/kWh), a battery storage size of 6 kWh would be

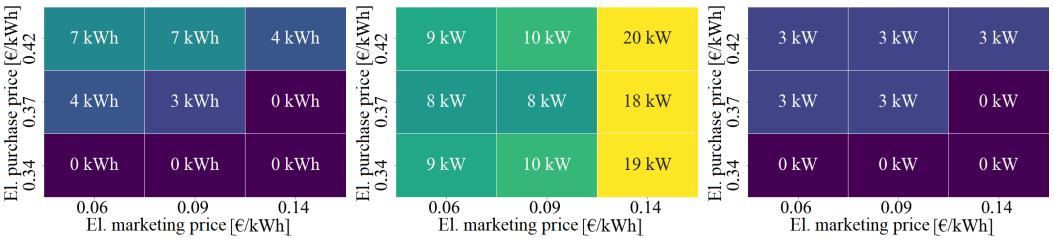
the most economical. At an electricity purchase price of 0.34 EUR/kWh and an electricity marketing price of 0.06 EUR/kWh and 0.14 EUR/kWh, as well as at an electricity purchase price of 0.37 EUR/kWh and an electricity marketing price of 0.14 EUR/kWh, a battery storage system does not make sense. With a 50% investment cost reduction, it can be seen with regard to the battery storage that it makes sense for all constellations. The optimal storage sizes would be between 4 kWh and 9 kWh, depending on the electricity purchase price, electricity marketing price, and PV system size. Looking at the detailed results in Table A4, it can also be seen that, if the investment cost of the small wind turbine is reduced by 25% and the battery storage is reduced by 50%, the most economic small wind turbine size would be the same as the variant of the investment cost reduction of the small wind turbine and battery storage by 50%. Thus, in this case, the battery storage investment cost has the greater impact. In the dimensioning of the PV system, the battery storage size shows relatively little influence on the dimensioning, except in the case of the battery storage investment cost reduction of 25% with an electricity marketing price of 0.06 EUR/kWh and an electricity purchase price of 0.37 EUR/kWh or 0.42 EUR/kWh. In this case, the reduction in the investment costs of the battery storage and the small wind turbine contributes to making the operation of a small wind turbine economical. Similarly, the installation of a battery storage greater than 5 kWh is unprofitable. This means that the PV system and the small wind turbine must share the limited storage capacity. Since wind power is prioritized here, this leads to smaller sizing of the PV system. The electricity marketing price also has a significant impact on the size of the PV system. In the most favorable case of an electricity marketing price of 0.14 EUR/kWh, a PV system size between 17 and 20 kWp would be the most economical. The optimal heat pump size is consistently 15 kW, and the optimal buffer storage sizes vary for heating and DHW storage between 0.5 m^3 and 1.0 m^3 for all combination possibilities.

3.8. Potsdam, Germany

Figure 11a–c show the optimal battery storage, PV system, and small wind turbine sizes for the Potsdam site for different electricity purchase and marketing prices, with an investment cost reduction of 25% for a small wind turbine and battery storage compared to today's prices. In Figure 12a–c, this is carried out for an investment cost reduction of 50%. Thereby, green and more yellow colors indicate that a large system is more economical. The detailed results showing the specific annual investment, maintenance, and energy costs, as well as the dimensioning of the additional system components (heat pump and heating and DHW buffer storage), are presented in the Appendix A in Table A5.

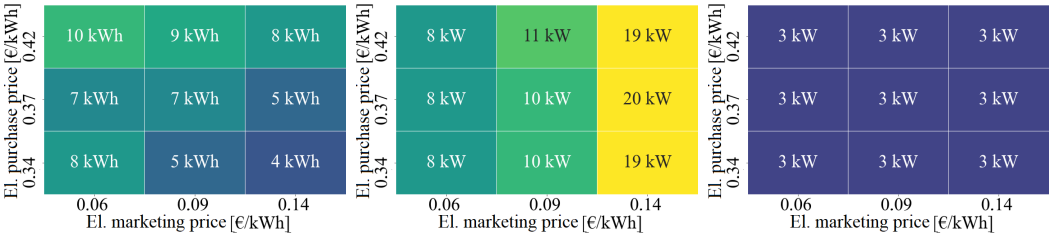
In the case of the Potsdam site, there are significant differences in the dimensioning depending on the investment cost reduction, especially for the battery storage size. Compared to the current situation in Table 3, a small wind turbine would make sense with an investment cost reduction of 25%, except for an electricity purchase price of 0.34 EUR/kWh and an electricity purchase price of 0.37 EUR/kWh in combination with an electricity marketing price of 0.14 EUR/kWh. The best small wind turbine size here would be 3 kW. For an investment cost reduction of 50%, the operation of a small wind turbine would make sense for all electricity purchases and electricity marketing price constellations. The best small wind turbine size would also be 3 kW. The optimal battery storage size at a 25% investment cost reduction is influenced by the expected yield, the electricity purchase price, and the electricity marketing price. At an investment cost reduction of 25%, a battery storage system only makes sense in combination with a small wind turbine. In the best case (3 kW small wind turbine; 9 kWp PV system; electricity purchase price of 0.42 EUR/kWh; electricity marketing price of 0.06 EUR/kWh), a battery storage size of 7 kWh would be the most economical. With a 50% investment cost reduction, it is shown with regard to the battery storage that its use is economical for all constellations. Depending on the electricity purchase price, electricity

marketing price, and PV system size, the optimal storage sizes would be between 4 kWh and 10 kWh. Looking at the detailed results in Table A4, it can be seen that, compared to the investment cost reduction of the battery storage, the investment cost reduction of the small wind turbine is the significant cause for the improvement in the economic efficiency of the hybrid system. In the PV system dimensioning, the battery storage size is shown to have a relatively small impact on the sizing. The electricity marketing price has the most significant impact on the PV system size. In the most favorable case of an electricity marketing price of 0.14 EUR/kWh, a PV system size between 18 and 20 kWp would be the most economical. The optimal heat pump size is consistently 15 kW, and the optimal buffer storage sizes vary between 0.5 m^3 and 0.8 m^3 for heating and DHW storage for all combination options.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

Figure 11. Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 25% for small wind turbine and battery storage, Potsdam site.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

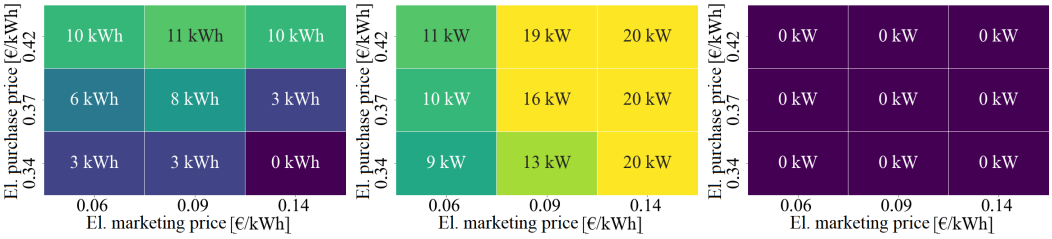
Figure 12. Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 50% for small wind turbine and battery storage, Potsdam site.

3.9. Stuttgart, Germany

Figure 13a–c show the optimal battery storage, PV system, and small wind turbine sizes for different electricity purchase and marketing prices for the Stuttgart site, with an investment cost reduction of 25% for a small wind turbine and battery storage compared to today's prices. In Figure 14a–c, this is carried out for an investment cost reduction of 50%. Thereby, green and more yellow colors indicate that a large system is more economical. The detailed results, showing the specific annual investment, maintenance, and energy costs, as well as the dimensioning results of the other systems (heat pump and heating and DHW buffer storage), are presented in the Appendix A in Table A6.

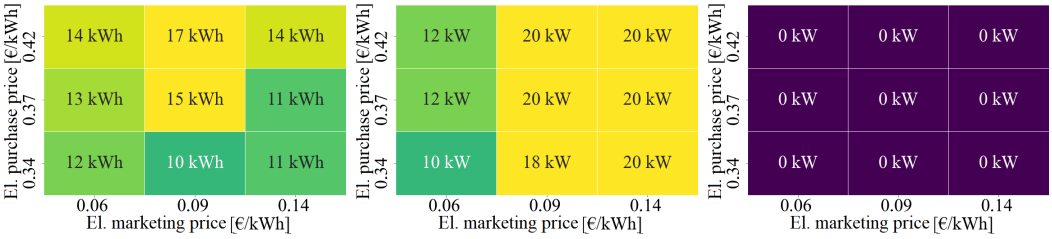
In the case of the Stuttgart site, there are significant differences in the dimensioning depending on the investment cost reduction, especially for the battery storage size. The operation of a small wind turbine would not be economical in any of the scenarios, as was already the case under the current framework conditions shown in Table 3. At a 25% investment cost reduction, the optimal battery storage size is influenced by the expected revenue, the electricity purchase price, and the electricity marketing price. At an investment cost reduction of 25%, a battery storage system does not make sense at an electricity purchase price of 0.34 EUR/kWh and an electricity marketing price of 0.14 EUR/kWh. For the other constellations, the most reasonable battery storage size varies between 3 kWh

and 11 kWh. With a 50% investment cost reduction, it can be seen with regard to the battery storage that its use is economical for all constellations. Depending on the electricity purchase price, electricity marketing price, and PV system size, the optimal storage sizes would be between 10 kWh and 17 kWh. When dimensioning the PV system, the battery storage size shows relatively little influence on the sizing. The electricity marketing price has the most significant impact on the PV system size. In the most favorable case of an electricity marketing price of 0.14 EUR/kWh, a PV system size of 20 kWp would be the most economical. The optimal heat pump size is consistently 15 kW, and the optimal buffer storage sizes vary between 0.5 m^3 and 1.1 m^3 for heating and DHW storage for all combination options.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

Figure 13. Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 25% for small wind turbine and battery storage, Stuttgart site.

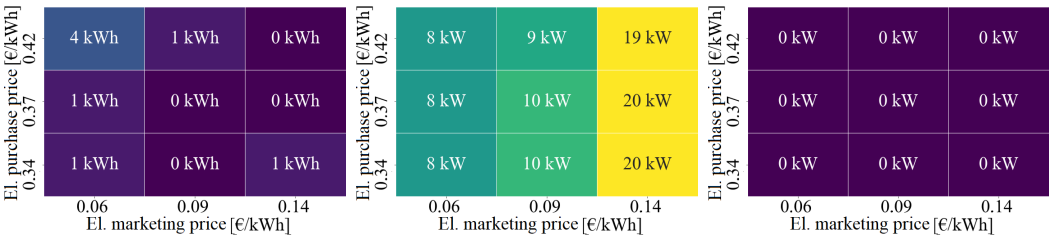


(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

Figure 14. Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 50% for small wind turbine and battery storage, Stuttgart site.

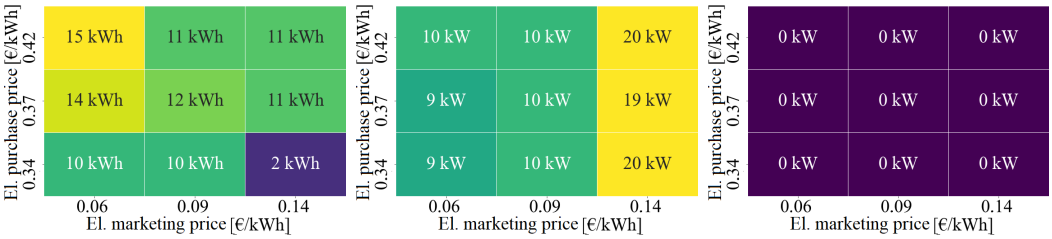
3.10. Wüstenrot, Germany

Figure 15a–c show the optimal battery storage, PV system, and small wind turbine sizes for the Wüstenrot site for different electricity purchase and marketing prices, with an investment cost reduction of a small wind turbine and battery storage by 25% compared to today's prices. In Figure 16a–c, this is carried out for an investment cost reduction of 50%. The detailed results, showing the specific annual investment, maintenance, and energy costs, as well as the dimensioning results of the other systems (heat pump and heating and DHW buffer storage), are presented in theAppendix A in Table A7.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

Figure 15. Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 25% for small wind turbine and battery storage, Wüstenrot site.



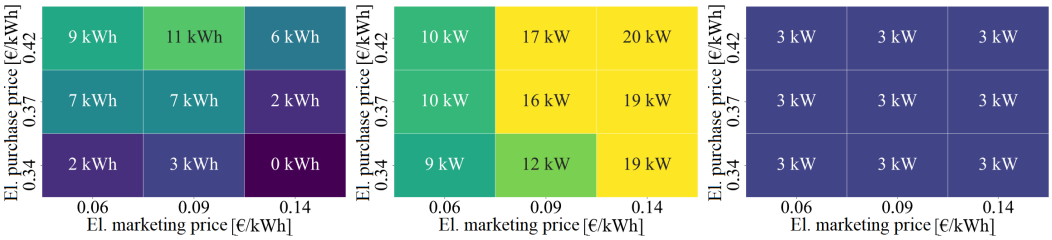
(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

Figure 16. Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 50% for small wind turbine and battery storage, Wüstenrot site.

In the case of the Wüstenrot site, there are significant differences in the dimensioning depending on the investment cost reduction, especially in the battery storage size. The operation of a small wind turbine would not be economical in any of the scenarios, as was already the case in the actual situation shown in Table 3. With an investment cost reduction of 25%, it can be seen that a battery storage system is hardly economical. Only at an electricity purchase price of 0.42 EUR/kWh and an electricity marketing price of 0.06 EUR/kWh is the battery storage dimensioned with 4 kWh. A 50% investment cost reduction results in the best case (electricity purchase price of 0.34 EUR/kWh and an electricity marketing price of 0.14 EUR/kWh) in battery storage sizes between 10 kWh and 15 kWh. When sizing the PV system, the battery storage size shows relatively little influence on the sizing. The electricity marketing price has the most significant impact on the PV system size. In the most favorable case of an electricity marketing price of 0.14 EUR/kWh, a PV system size of 19–20 kWp would be the most economical. The optimal heat pump size is consistently 15 kW, and the optimal buffer storage sizes vary between 0.5 m^3 and 1.3 m^3 for heating and DHW storage for all combination options.

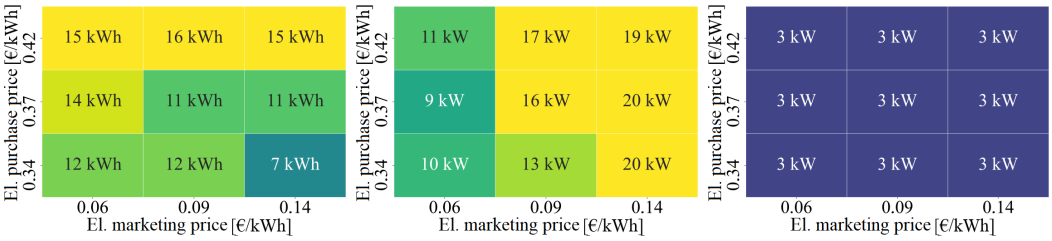
3.11. Montreal, Canada

Figure 17a–c show the optimal battery storage, PV system, and small wind turbine sizes for the Montreal site for different electricity purchase and marketing prices, with a 25% investment cost reduction of a small wind turbine and battery storage compared to today's prices. In Figure 18a–c, this is carried out for an investment cost reduction of 50%. Thereby, green and more yellow colors indicate that a large system is more economical. The detailed results, showing the specific annual investment, maintenance, and energy costs, as well as the dimensioning results of the other systems (heat pump and heating and DHW buffer storage), are presented in the Appendix A in Table A8.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

Figure 17. Optimal system component sizes for a single-family home as a function of electricity purchase and marketing price with an investment cost reduction of 25% for small wind turbine and battery storage, Montreal site.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

Figure 18. Optimal system component sizes for a single-family home as a function of electricity purchase and marketing price with an investment cost reduction of 50% for small wind turbine and battery storage, Montreal site.

In the case of the Montreal site, there are clear differences in the dimensioning depending on the investment cost reduction for the battery storage size, as well as for the dimensioning of the PV system. Compared to the current situation in Table 3, a small wind turbine would make sense for all combination options with an investment cost reduction of 25% and larger. The best small wind turbine size here would be 3 kW. The optimal battery storage size at a 25% investment cost reduction is influenced by the expected yield, the electricity purchase price, and the electricity marketing price. In the best case (3 kW small wind turbine; 17 kWp PV system; electricity purchase price of 0.42 EUR/kWh; electricity marketing price of 0.09 EUR/kWh), a battery storage size of 11 kWh would be the most economical. With an electricity purchase price of 0.34 EUR/kWh and an electricity marketing price of 0.14 EUR/kWh, a battery storage system does not make sense. With a 50% investment cost reduction, it is shown with regard to the battery storage that it makes sense for all constellations. The optimal storage sizes would be between 7 kWh and 16 kWh, depending on the electricity purchase price, electricity marketing price, and PV system size. Looking at the detailed results in Table A8, we see that, in the limiting case (25% small wind turbine and 50% battery storage investment cost reduction), where the heat pump was sized to 18 kW by the algorithm, a larger small wind turbine of 7 kW would be most economical. The PV system dimensioning shows relatively little influence on the dimensioning of the battery storage. The electricity marketing price has the most significant impact on the size of the PV system. In the most favorable case of an electricity marketing price of 0.14 EUR/kWh, a PV system size between 19 and 20 kWp would be the most economical. The optimal heat pump size is between 15 kW and 18 kW, and the optimal buffer storage sizes vary between 0.5 m^3 and 0.9 m^3 for heating and DHW storage for all possible combinations.

4. Discussion

For the optimized sizing of a hybrid energy supply system (consisting of a heat pump, buffer storage, battery storage, PV system, and small wind turbine) for a single-family house, the best parameters for the genetic optimization algorithm were first determined iteratively. This resulted in an optimal crossover probability of $0.7 \leq p_c \leq 1.0$ in conjunction with an optimal mutation probability of $0.4 \leq p_m \leq 0.5$, with the best number of generations being 30 and the best population size being 90. Furthermore, competition selection with a tournament size of 5 was chosen as the selection method. Based on this, the system components were dimensioned for different scenarios for different locations with and without the integration of a BEV using vehicle-to-home under the current framework conditions. Under future framework conditions, different electricity purchase and electricity marketing prices were included in the dimensioning, with a gradual reduction in the investment costs of the small wind turbine and battery storage.

4.1. Current Framework Conditions

The dimensioning for the current state shows that small wind turbines can only be operated economically in the locations with high wind potential, such as Aachen and Montreal. The same holds for the battery storage, which, despite an installed PV system and heat pump operation, would only be economical in the case of an additional small wind turbine and, even then, only at a very small size (1–2 kWh). The size of the heating buffer storage is normal at 0.5–0.8 m^3. The PV system is sized between 4 and 9 kWp depending on the irradiation of the location.

In Figure 19, the mean value of the dimensioned system size of the battery storage, PV system, and small wind turbine is shown for the different German locations and compared with the replacement of the battery storage by the vehicle-to-home use of a BEV with two different driving profiles. Here, the V2H 1 driving profile means use as a first car with a weekday commute to work, and the V2H 2 driving profile means use as a second car with longer periods of availability and lower charging requirements. It is assumed that 16 kWh of the vehicle battery can be used, which corresponds to the range between 40% and 60% of the SOC for an 80 kWh battery. On average, a 49% larger PV system would make sense due to vehicle-to-home operation compared to the dimensioning without the BEV. At the same time, the current conditions do not show a positive impact on the size of the small wind turbine. In the case of the Montreal site, the economics of a small wind turbine actually become worse, which can be attributed to the lower availability and efficiency of the vehicle battery charging and discharging process compared to a stationary battery storage system. However, under future conditions, the impact of a vehicle-to-home application could have a positive effect on the sizing of a small wind turbine. This needs to be investigated further and was not considered in the context of this work.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

Figure 19. Optimal system component sizes for a single-family house, current state without and with vehicle-to-home use, mean values across all locations studied in Germany.

A positive aspect of the vehicle-to-home application is that, due to the increased self-consumption, the electricity costs remain the same or decrease, depending on the driving profile, despite additional power requirements of 2410.7 kWh (first car) or 1366.3 kWh (second car). It should be noted that this study did not take into account the additional costs related to battery aging. According to a previous study, this would be between EUR 175.5 and EUR 271.6 per year, depending on the driving profile. In this context, however, it must also be considered that bidirectional operation takes place in the range of a state of charge (SOC) between 40% and 60%, which means a high cycle stability and thus the vehicle's age possibly being reached earlier despite vehicle-to-home operation, rather than the vehicle battery falling below 80% in capacity [46].

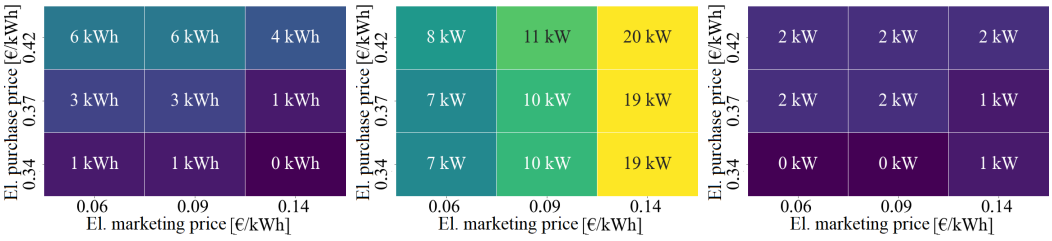
4.2. Future Framework Conditions

With regard to the future scenarios examined, it should be noted that no investment cost reductions were assumed for the PV system, since the prices here have already reached a very low level, whereas larger cost reductions can be assumed for battery storage and possibly also for the small wind turbine due to economies of scale and new technologies.

In addition, it must be taken into account that the dimensioning of the small wind turbine is not representative of the average values over several locations due to the influence of local conditions (buildings, vegetation, topography). The dimensioning of the PV system and, in connection with it, the battery storage is clearly more independent of this and gives more general insights.

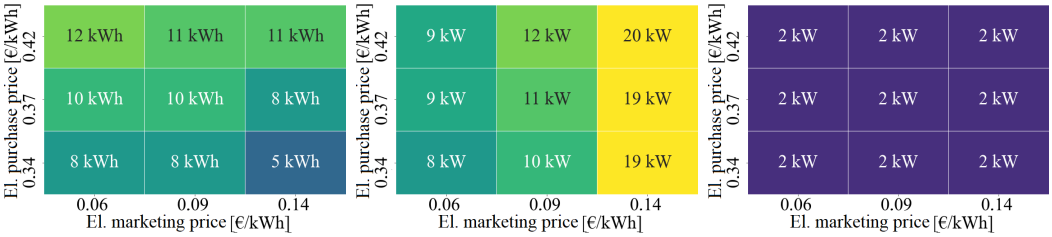
When dimensioning the small wind turbine, it becomes apparent that turbines of a smaller size are preferred since their performance values differ little at low wind speeds (2.5–4 m/s) (see Figure 3), whereas the costs increase disproportionately in comparison. The interaction between costs (see Figure 2) and characteristics (see Figure 3) also explains why the dimensioning of the small wind turbine converges at 3 kW for the sites with higher wind potential. This size offers the best ratio of yield to investment costs at the prevailing wind speeds, since investment costs increase disproportionately between a 3 kW and 5 kW turbine size. In general, the annual costs are close to each other. For example, at the Aachen site, an increase in the size of the small wind turbine from 3 kW to 4 kW would mean an increase in costs of 7%.

Figure 20 shows different scenarios for electricity purchase and electricity marketing prices, averaged over all German locations, with an investment cost reduction of 25% for the battery storage and small wind turbine. Figure 21 shows the same averaged scenarios with an investment cost reduction of 50%. In general, it can be seen that, with regard to the dimensioning of the PV system, the electricity marketing price is mainly decisive. The electricity purchase price as well as the battery storage size have a subordinate effect. This is due to the fact that the demand of the building and thus the maximum achievable self-consumption are limiting factors.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

Figure 20. Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 25% for small wind turbine and battery storage, average values across all locations investigated in Germany.



(**a**) Optimal battery storage size. (**b**) Optimal PV system size. (**c**) Optimal wind turbine size.

Figure 21. Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 50% for small wind turbine and battery storage, average values across all locations investigated in Germany.

With regard to the dimensioning of the small wind turbine, interestingly, the electricity purchase price has the greater effect. This can be explained by the fact that the small wind turbine enables a significantly higher share of self-consumption of wind-generated electricity due to the higher simultaneity of generation and consumption, as well as the

preferential use of wind electricity in the model. A reduction in the investment costs also has a noticeable effect, whereby, at higher electricity purchase prices of ≥0.37 EUR/kWh, an investment cost reduction of 25% already has the same effect as an investment cost reduction of 50%.

With regard to the dimensioning of the battery storage system, it can be seen that the electricity purchase price and the electricity marketing price have an equal influence on its economic efficiency. In addition, a reduction in the investment costs to 25% as well as to 50% has a significant effect on the dimensioning. If a battery storage would still be almost unprofitable with an investment cost reduction of 25%, at favorable electricity purchase prices of 0.34 EUR/kWh, battery storage sizes of 5–12 kWh would be most economical with an investment cost reduction of 50%.

With regard to the heat pump and the buffer storage, it is shown that there is hardly any effect of the different climatic conditions on their dimensioning. It is also shown that the original dimensioning of the heat pump of the building was oversized, whereas the thermal buffer storages are similar in size to the original building. However, it should also be noted here that, in reality, the heating capacity is dimensioned to be somewhat larger for extreme situations.

Finally, it should be mentioned that variations in dimensioning are possible, since genetic algorithms find a global optimum only approximately. This can lead to fluctuations in components with low investment costs, such as buffer storage sizes.

4.3. Conclusions

Our observations indicate that higher electricity procurement costs, specifically those exceeding 0.42 EUR/kWh, in combination with a 25% reduction in investment expenses for small wind turbines and battery storage systems, have the potential to significantly improve the economic viability of small wind turbines supplying residential buildings equipped with heat pumps. In such scenarios, small wind turbines could become appealing for a wider range of locations. In many cases, the current feed-in tariff or the option of direct marketing at electricity prices exceeding 60 EUR/MWh would be sufficient for ensuring economically viable operations. At the same time, considering the increasing electrification of the transportation sector and the increasing potential of bidirectional charging, it has been demonstrated that, within the current framework conditions, the integration of battery electric vehicles (BEVs) and bidirectional charging does not have a positive impact on the economic feasibility of the discussed small wind turbine installations. However, looking ahead to future conditions, effective load management for heat pumps or BEV charging could potentially contribute to the profitability of small wind turbines.

Author Contributions: M.B., R.O. and B.S. wrote the main manuscript. All authors reviewed the manuscript. The design of the work, its analysis, and the interpretation of data were carried out by M.B. and D.P., D.P. and U.E. revised this work critically for important intellectual content. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Federal Ministry for Economic Affairs and Climate Action grant number 03ET1116A within the research project Smart2Charge.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Marcus Brennenstuhl was employed by the company Enisyst GmbH. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BEV	Battery Electric Vehicle
C_{batt}	Battery Capacity [kWh]
c_i	Sum of electricity purchase or sale [€]
CFD	Computational Fluid Dynamics
DWD	Deutscher Wetterdienst (German Weather Service)
DHW	Domestic Hot Water
EA	Evolutionary Algorithm
EAC	Equivalent Annual Cost (economic evaluation)
$ECCC$	Environment and Climate Change Canada
GA	Genetic Algorithm
HP	Heat Pump
$INSEL$	Integrated Simulation Environment Language
n_{Life}	Estimated lifetime of the investment in years
OM	Operating and Maintenance Costs [€]
P	Annualized Capital Cost [€]
p_c	Probability of crossover in genetic algorithms
P_{el}	Electrical Power [kW]
p_m	Probability of mutation in genetic algorithms
P_{th}	Thermal Power [kW]
PSO	Particle Swarm Optimization
PV	Photovoltaic
PV	Present Value (for investment) [€]
Q_i	Amount of energy [kWh]
r_i	Interest rate per period (e.g., annually)
RE	Renewable Energy
RES	Renewable Energy Source
SA	Simulated Annealing
SOC	State of Charge
VDI	Verein Deutscher Ingenieure (Association of German Engineers)
$V2H$	Vehicle-to-Home

Appendix A. Detailed Dimensioning Results

Table A1. Size-specific investment costs of different energy supply systems. Cost sources: (a) [51] small wind turbine type Aeolos-V incl. 43% costs for foundation, mast and installation; (b) [52] incl. inverter and installation; (c) [53]; (d) own research of current trade prices incl. EUR 2500 installation costs; (e) own research of current trade prices incl. EUR 1000 installation costs.

Small Wind Turbine			
System Size [kW]	**Invest [EUR]** [(a)]	**Maintenance Cost**	**Life Span**
1 kW	7254	3.0%	20 years
3 kW	13,549		
5 kW	25,000		
10 kW	34,658		
20 kW	53,130		
PV system			
System size [kW]	**Invest [EUR]** [(b)]	**Maintenance cost**	**Life span**
4	6400	2.3%	20 years
6	9360		
8	11,040		
10	13,300		
15	19,800		
20	25,800		

Table A1. *Cont.*

Battery storage			
System size [kW]	**Invest [EUR]** [(c)]	**Maintenance cost**	**Life span**
0	1800	2.3%	15 years
5	5500		
10	9000		
15	12,000		
20	15,000		
Heat pump			
System size [kW]	**Invest [EUR]** [(d)]	**Maintenance cost**	**Life span**
0	11,100	3.5%	20 years
4	11,100		
10	12,500		
15	14,500		
20	16,000		
Thermal buffer storage			
System size [Ł]	**Invest [EUR]** [(e)]	**Maintenance cost**	**Life span**
200	1200	3.0%	20 years
500	1500		
1000	2500		
1500	2600		
2000	2700		
3000	3600		

Table A2. Optimized dimensioning and economic efficiency of the energy supply system of a single building for electricity price and investment cost scenarios, Aachen site.

Total Cost [EUR/a]	**Energy Cost [EUR/a]**	**Invest./ Maintenance [EUR/a]**	**P_{th} HP [kW]**	**$V_{storage}$ DHW [m³]**	**$V_{storage}$ Room [m³]**	**C_{batt} [kWh]**	**P_{el} PV [kWp]**	**P_{el} Wind [kW]**	**El. Marketing Price [EUR/kWh]**	**El. Purchase Price [EUR/kWh]**
Investment Cost Reduction of Small Wind Turbine by 25%; Battery Storage by 25%										
6760	1669	5091	15	0.5	0.7	4	4	3	0.06	0.34
6805	1667	5138	15	0.5	0.7	4	5	3	0.06	0.37
6999	1372	5626	15	0.5	0.5	8	8	3	0.06	0.42
6643	1208	5435	15	0.9	0.6	2	9	3	0.09	0.34
6647	1161	5486	15	0.5	0.5	4	9	3	0.09	0.37
6868	1140	5728	15	0.5	0.5	8	9	3	0.09	0.42
6019	−222	6241	15	0.5	0.5	0	19	3	0.14	0.34
6363	−406	6768	15	0.5	0.5	2	18	4	0.14	0.37
6379	−358	6737	15	0.5	0.5	6	19	3	0.14	0.42
Investment cost reduction of small wind turbine by 50%; battery storage by 25%										
6309	1708	4601	15	0.5	0.7	3	4	3	0.06	0.34
6558	1847	4710	15	0.5	0.5	5	3	3	0.06	0.37
6677	1324	5353	15	0.5	0.5	9	8	3	0.06	0.42
6301	1134	5167	15	0.8	0.5	4	8	3	0.09	0.34
6314	1259	5055	15	0.5	0.5	4	8	3	0.09	0.37
6548	1093	5455	15	0.5	0.5	9	9	3	0.09	0.42
5832	−319	6150	15	0.6	0.7	0	20	3	0.14	0.34
5881	−489	6371	15	0.6	0.7	3	20	3	0.14	0.37
6145	−284	6430	15	0.8	0.7	4	19	3	0.14	0.42

Table A2. *Cont.*

Total Cost [EUR/a]	Energy Cost [EUR/a]	Invest./ Maintenance [EUR/a]	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	El. Marketing Price [EUR/kWh]	El. Purchase Price [EUR/kWh]
Investment cost reduction of small wind turbine by 25%; battery storage by 50%										
6513	1374	5140	15	0.5	0.7	7	5	3	0.06	0.34
6598	1486	5112	15	0.5	0.5	11	4	3	0.06	0.37
6863	1039	5824	15	0.5	0.8	12	10	3	0.06	0.42
6388	724	5664	15	0.5	0.5	12	9	3	0.09	0.34
6529	946	5584	15	0.6	0.7	8	9	3	0.09	0.37
6768	975	5793	15	0.8	0.7	13	9	3	0.09	0.42
5980	−688	6668	15	0.8	0.5	7	19	3	0.14	0.34
6069	−745	6813	15	0.8	0.5	8	20	3	0.14	0.37
6340	−93	6433	15	0.5	0.7	8	16	3	0.14	0.42
Investment cost reduction of small wind turbine by 50%; battery storage by 50%										
6321	1486	4835	15	0.8	0.5	8	4	3	0.06	0.34
6260	1091	5169	15	0.5	0.5	10	8	3	0.06	0.37
6563	1360	5203	15	0.9	0.5	11	7	3	0.06	0.42
6107	880	5227	15	0.6	0.7	10	8	3	0.09	0.34
6135	1004	5131	15	0.5	0.5	9	8	3	0.09	0.37
6380	917	5463	15	0.6	0.7	11	10	3	0.09	0.42
5588	−692	6280	15	0.5	0.5	7	19	3	0.14	0.34
5681	−599	6280	15	0.5	0.5	7	19	3	0.14	0.37
5846	−718	6564	15	0.5	0.5	12	20	3	0.14	0.42

Table A3. Optimized dimensioning and economic efficiency of the energy supply system of a single building for electricity price and investment cost scenarios. Braunlage site.

Total Cost [EUR/a]	Energy Cost [EUR/a]	Invest./ Maintenance [EUR/a]	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	El. Marketing Price [EUR/kWh]	El. Purchase Price [EUR/kWh]
Investment Cost Reduction of Small Wind Turbine by 25%; Battery Storage by 25%										
7812	4182	3631	15	0.5	0.6	0	4	0	0.06	0.34
8233	4106	4127	15	0.9	0.6	0	8	0	0.06	0.37
8720	4433	4287	15	0.5	0.7	2	8	0	0.06	0.42
7806	3596	4209	15	0.5	0.9	0	9	0	0.09	0.34
8104	3641	4463	15	0.5	0.7	3	9	0	0.09	0.37
8653	3359	5294	15	0.5	0.8	2	8	3	0.09	0.42
7454	2143	5311	15	0.5	0.8	0	19	0	0.14	0.34
7785	2221	5564	15	0.5	0.8	1	20	0	0.14	0.37
8265	1604	6661	15	0.5	0.6	3	20	3	0.14	0.42
Investment cost reduction of small wind turbine by 50%; battery storage by 25%										
7774	3075	4699	15	0.8	0.6	2	5	3	0.06	0.34
8005	3345	4659	15	0.7	0.8	3	4	3	0.06	0.37
8400	3665	4734	15	0.5	0.7	3	5	3	0.06	0.42
7648	2601	5047	15	0.6	0.6	2	9	3	0.09	0.34
7968	2843	5125	15	0.9	0.7	2	9	3	0.09	0.37
8305	3360	4945	15	0.5	0.7	2	8	3	0.09	0.42
7304	1353	5951	15	0.5	0.7	0	19	3	0.14	0.34
7508	1794	5715	15	0.5	0.6	0	17	3	0.14	0.37
8003	1613	6390	15	0.5	0.9	3	20	3	0.14	0.42

Table A3. *Cont.*

Total Cost [EUR/a]	Energy Cost [EUR/a]	Invest./ Maintenance [EUR/a]	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	El. Marketing Price [EUR/kWh]	El. Purchase Price [EUR/kWh]
Investment cost reduction of small wind turbine by 25%; battery storage by 50%										
7840	4025	3815	15	0.6	0.7	2	4	0	0.06	0.34
8062	3277	4785	15	0.5	0.7	11	10	0	0.06	0.37
8501	3703	4798	15	0.5	0.6	12	10	0	0.06	0.42
7768	3145	4623	15	0.6	0.7	6	10	0	0.09	0.34
7960	3339	4621	15	0.5	0.6	7	10	0	0.09	0.37
8469	2657	5812	15	0.6	0.8	11	10	3	0.09	0.42
7419	2109	5310	15	0.5	0.6	2	18	0	0.14	0.34
7746	1334	6412	15	0.5	0.6	7	17	3	0.14	0.37
8105	2224	5881	15	0.5	0.7	10	20	0	0.14	0.42
Investment cost reduction of small wind turbine by 50%; battery storage by 50%										
7597	3094	4503	15	0.5	0.7	3	4	3	0.06	0.34
7838	2611	5227	15	0.6	0.7	10	8	3	0.06	0.37
8152	2830	5322	15	0.5	0.6	11	9	3	0.06	0.42
7544	2448	5096	15	0.5	0.7	7	8	3	0.09	0.34
7761	2405	5356	15	0.7	0.6	8	10	3	0.09	0.37
8141	2659	5482	15	0.7	0.7	11	10	3	0.09	0.42
7291	1018	6273	15	0.5	0.8	3	20	3	0.14	0.34
7410	1036	6374	15	0.5	0.6	9	19	3	0.14	0.37
7777	1346	6431	15	0.5	0.7	10	19	3	0.14	0.42

Table A4. Optimized dimensioning and economic efficiency of the energy supply system of a single building for electricity price and investment cost scenarios. Greifswald site.

Total Cost [EUR/a]	Energy Cost [EUR/a]	Invest./ Maintenance [EUR/a]	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	El. Marketing Price [EUR/kWh]	El. Purchase Price [EUR/kWh]
Investment Cost Reduction of Small Wind Turbine by 25%; Battery Storage by 25%										
7457	3388	4069	15	0.5	0.7	0	8	0	0.06	0.34
7646	2770	4876	15	0.5	0.8	2	4	3	0.06	0.37
8034	2785	5248	15	0.5	0.6	6	5	3	0.06	0.42
7427	3175	4252	15	0.6	0.8	1	8	0	0.09	0.34
7508	2272	5236	15	0.5	0.5	2	8	3	0.09	0.37
7913	2407	5505	15	0.6	0.5	4	9	3	0.09	0.42
6872	631	6241	15	0.5	0.5	0	19	3	0.14	0.34
7081	1057	6024	15	0.5	0.5	0	17	3	0.14	0.37
7482	802	6680	15	0.5	0.7	3	20	3	0.14	0.42
Investment cost reduction of small wind turbine by 50%; battery storage by 25%										
7040	2552	4488	15	0.5	0.5	2	4	3	0.06	0.34
7352	2767	4585	15	0.5	1	2	4	3	0.06	0.37
7628	3140	4488	15	0.5	0.5	2	4	3	0.06	0.42
6979	2491	4488	15	0.5	0.5	2	4	3	0.09	0.34
7241	2585	4656	15	0.5	0.6	4	4	3	0.09	0.37
7580	2506	5074	15	0.6	0.5	4	8	3	0.09	0.42
6600	525	6075	15	0.5	0.6	1.0	19	3	0.14	0.34
6811	841	5970	15	0.5	0.8	0	19	3	0.14	0.37
7141	1100	6041	15	0.5	0.6	2	18	3	0.14	0.42

Table A4. *Cont.*

Total Cost [EUR/a]	Energy Cost [EUR/a]	Invest./ Maintenance [EUR/a]	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	El. Marketing Price [EUR/kWh]	El. Purchase Price [EUR/kWh]
Investment cost reduction of small wind turbine by 25%; battery storage by 50%										
7292	2324	4967	15	0.5	0.5	7	4	3	0.06	0.34
7467	2499	4967	15	0.5	0.5	7	4	3	0.06	0.37
7838	2395	5443	15	0.6	0.5	8	8	3	0.06	0.42
7255	1887	5368	15	0.5	0.6	6	8	3	0.09	0.34
7447	1781	5666	15	0.6	0.6	8	10	3	0.09	0.37
7751	2047	5703	15	0.6	0.6	9	10	3	0.09	0.42
6934	247	6687	15	0.8	0.6	7	19	3	0.14	0.34
6987	340	6647	15	0.5	0.5	8	19	3	0.14	0.37
7305	601	6703	15	0.6	0.5	9	19	3	0.14	0.42
Investment cost reduction of small wind turbine by 50%; battery storage by 50%										
7047	1711	5335	15	0.5	0.5	9	10	3	0.06	0.34
7225	2054	5170	15	0.7	0.5	9	8	3	0.06	0.37
7470	2338	5131	15	0.5	0.5	9	8	3	0.06	0.42
6932	1980	4952	15	0.6	0.5	4	8	3	0.09	0.34
7056	1897	5159	15	0.5	0.5	7	9	3	0.09	0.37
7364	2066	5298	15	0.5	0.5	8	10	3	0.09	0.42
6556	420	6136	15	0.5	0.7	5	18	3	0.14	0.34
6655	375	6280	15	0.5	0.5	7	19	3	0.14	0.37
7004	610	6394	15	0.6	0.6	9	19	3	0.14	0.42

Table A5. Optimized dimensioning and economic efficiency of the energy supply system of a single building for electricity price and investment cost scenarios. Potsdam site.

Total Cost [EUR/a]	Energy Cost [EUR/a]	Invest./ Maintenance [EUR/a]	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	El. Marketing Price [EUR/kWh]	El. Purchase Price [EUR/kWh]
Investment Cost Reduction of Small Wind Turbine by 25%; Battery Storage by 25%										
7349	3198	4151	15	0.5	0.6	0	9	0	0.06	0.34
7592	2169	5423	15	0.7	0.5	4	8	3	0.06	0.37
7932	2221	5711	15	0.6	0.6	7	9	3	0.06	0.42
7207	2954	4253	15	0.6	0.5	0	10	0	0.09	0.34
7419	2109	5310	15	0.5	0.5	3	8	3	0.09	0.37
7769	1975	5793	15	0.5	0.6	7	10	3	0.09	0.42
6705	1413	5292	15	0.7	0.5	0	19	0	0.14	0.34
6941	1776	5164	15	0.6	0.5	0	18	0	0.14	0.37
7335	541	6793	15	0.8	0.6	4	20	3	0.14	0.42
Investment cost reduction of small wind turbine by 50%; battery storage by 25%										
7035	2266	4770	15	0.5	0.5	4	5	3	0.06	0.34
7226	2511	4715	15	0.6	0.5	3	5	3	0.06	0.37
7533	2349	5185	15	0.5	0.5	6	8	3	0.06	0.42
6944	1740	5204	15	0.6	0.5	3	10	3	0.09	0.34
7086	2179	4907	15	0.5	0.5	2	8	3	0.09	0.37
7436	2028	5408	15	0.5	0.6	6	10	3	0.09	0.42
6597	352	6245	15	0.5	0.6	1	18	4	0.14	0.34
6596	556	6039	15	0.5	0.6	0	20	3	0.14	0.37
6971	694	6277	15	0.6	0.6	2	20	3	0.14	0.42

Table A5. *Cont.*

Total Cost [EUR/a]	Energy Cost [EUR/a]	Invest./ Maintenance [EUR/a]	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	El. Marketing Price [EUR/kWh]	El. Purchase Price [EUR/kWh]
Investment cost reduction of small wind turbine by 25%; battery storage by 50%										
7225	2594	4632	15	0.5	0.6	10	9	0	0.06	0.34
7405	2659	4746	15	0.5	0.5	11	10	0	0.06	0.37
7668	2245	5423	15	0.5	0.5	8	8	3	0.06	0.42
7127	2468	4659	15	0.5	0.6	8	10	0	0.09	0.34
7352	1713	5639	15	0.6	0.6	10	9	3	0.09	0.37
7644	1735	5910	15	0.8	0.5	11	11	3	0.09	0.42
6667	918	5749	15	0.6	0.5	7	20	0	0.14	0.34
6822	228	6593	15	0.5	0.5	4	20	3	0.14	0.37
7072	279	6792	15	0.5	0.5	9	20	3	0.14	0.42
Investment cost reduction of small wind turbine by 50%; battery storage by 50%										
6898	1804	5094	15	0.5	0.5	8	8	3	0.06	0.34
7073	1997	5076	15	0.6	0.5	7	8	3	0.06	0.37
7364	2176	5188	15	0.5	0.6	10	8	3	0.06	0.42
6813	1627	5186	15	0.5	0.5	5	10	3	0.09	0.34
6946	1685	5261	15	0.5	0.5	7	10	3	0.09	0.37
7257	1785	5472	15	0.5	0.6	9	11	3	0.09	0.42
6345	189	6156	15	0.5	0.5	4	19	3	0.14	0.34
6491	178	6314	15	0.5	0.5	5	20	3	0.14	0.37
6770	434	6337	15	0.6	0.5	8	19	3	0.14	0.42

Table A6. Optimized dimensioning and economic efficiency of the energy supply system of a single building for electricity price and investment cost scenarios. Stuttgart site.

Total Cost [EUR/a]	Energy Cost [EUR/a]	Invest./ Maintenance [EUR/a]	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	El. Marketing Price [EUR/kWh]	El. Purchase Price [EUR/kWh]
Investment Cost Reduction of Small wind Turbine by 25%; Battery Storage by 25%										
6810	2386	4424	15	0.5	0.5	3	9	0	0.06	0.34
6992	2262	4730	15	0.5	0.5	6	10	0	0.06	0.37
7346	2255	5091	15	0.6	0.5	10	11	0	0.06	0.42
6728	1830	4897	15	0.6	0.5	3	13	0	0.09	0.34
6851	1314	5537	15	0.5	0.5	8	16	0	0.09	0.37
7176	1096	6080	15	0.5	0.8	11	19	0	0.09	0.42
5970	570	5400	15	0.6	0.6	0	20	0	0.14	0.34
6260	474	5786	15	0.8	0.6	3	20	0	0.14	0.37
6493	411	6082	15	0.5	0.5	10	20	0	0.14	0.42
Investment cost reduction of small wind turbine by 50%; battery storage by 25%										
6818	2542	4276	15	0.5	0.5	1	9	0	0.06	0.34
6990	2030	4959	15	0.5	0.5	8	11	0	0.06	0.37
7304	2067	5237	15	0.5	0.5	11	12	0	0.06	0.42
6710	2437	4273	15	0.6	0.6	0	10	0	0.09	0.34
6898	1511	5387	15	0.6	0.5	9	14	0	0.09	0.37
7171	1062	6109	15	0.5	0.7	12	19	0	0.09	0.42
5912	550	5361	15	0.5	0.5	0	20	0	0.14	0.34
6175	775	5400	15	0.7	0.5	0	20	0	0.14	0.37
6509	464	6045	15	0.5	0.6	9	20	0	0.14	0.42

Table A6. *Cont.*

Total Cost [EUR/a]	Energy Cost [EUR/a]	Invest./ Maintenance [EUR/a]	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	El. Marketing Price [EUR/kWh]	El. Purchase Price [EUR/kWh]
Investment cost reduction of small wind turbine by 25%; battery storage by 50%										
6620	1854	4766	15	0.5	0.6	11	10	0	0.06	0.34
6802	1965	4836	15	0.5	0.8	12	10	0	0.06	0.37
7074	1927	5148	15	0.5	0.7	15	12	0	0.06	0.42
6476	646	5830	15	0.5	0.5	13	19	0	0.09	0.34
6637	756	5881	15	0.6	0.5	14	19	0	0.09	0.37
6842	744	6098	15	0.5	0.5	18	20	0	0.09	0.42
6028	164	5865	15	1.1	0.5	11	19	0	0.14	0.34
5987	113	5874	15	0.5	0.5	11	20	0	0.14	0.37
6239	365	5874	15	0.5	0.5	11	20	0	0.14	0.42
Investment cost reduction of small wind turbine by 50%; battery storage by 50%										
6593	1815	4778	15	0.5	0.5	12	10	0	0.06	0.34
6752	1707	5045	15	0.5	0.5	13	12	0	0.06	0.37
7025	1949	5077	15	0.5	0.5	14	12	0	0.06	0.42
6488	863	5625	15	0.5	0.5	10	18	0	0.09	0.34
6601	599	6002	15	0.5	0.5	15	20	0	0.09	0.37
6835	769	6066	15	0.5	0.5	17	20	0	0.09	0.42
5861	−13	5874	15	0.5	0.5	11	20	0	0.14	0.34
5987	113	5874	15	0.5	0.5	11	20	0	0.14	0.37
6248	259	5989	15	0.5	0.6	14	20	0	0.14	0.42

Table A7. Optimized dimensioning and economic efficiency of the energy supply system of a single building for electricity price and investment cost scenarios. Wüstenrot site.

Total Cost [EUR/a]	Energy Cost [EUR/a]	Invest./ Maintenance [EUR/a]	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	El. Marketing Price [EUR/kWh]	El. Purchase Price [EUR/kWh]
Investment Cost Reduction of Small Wind Turbine by 25%; Battery Storage by 25%										
7606	3355	4252	15	0.7	0.7	1	8	0	0.06	0.34
7931	3621	4310	15	0.8	0.9	1	8	0	0.06	0.37
8333	3898	4435	15	0.6	0.6	4	8	0	0.06	0.42
7369	3135	4234	15	0.5	0.5	0	10	0	0.09	0.34
7707	3396	4311	15	0.5	0.9	0	10	0	0.09	0.37
8251	3917	4334	15	0.6	0.7	1	9	0	0.09	0.42
7038	1494	5544	15	0.6	0.6	1	20	0	0.14	0.34
7174	1813	5361	15	0.5	0.5	0	20	0	0.14	0.37
7685	2432	5253	15	0.5	0.5	0	19	0	0.14	0.42
Investment cost reduction of small wind turbine by 50%; battery storage by 25%										
7455	3844	3611	15	0.5	0.5	0	4	0	0.06	0.34
7778	3428	4350	15	0.5	0.5	2	9	0	0.06	0.37
8304	3498	4806	15	0.6	0.5	7	10	0	0.06	0.42
7476	2986	4491	15	0.7	0.5	2	10	0	0.09	0.34
7680	3283	4397	15	0.5	0.6	1	10	0	0.09	0.37
8258	3947	4311	15	0.6	0.8	0	10	0	0.09	0.42
6962	1798	5164	15	0.6	0.5	0	18	0	0.14	0.34
7195	1922	5273	15	0.5	0.6	0	19	0	0.14	0.37
7698	2426	5273	15	0.5	0.6	0	19	0	0.14	0.42

Table A7. *Cont.*

Total Cost [EUR/a]	Energy Cost [EUR/a]	Invest./ Maintenance [EUR/a]	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	El. Marketing Price [EUR/kWh]	El. Purchase Price [EUR/kWh]
Investment cost reduction of small wind turbine by 25%; battery storage by 50%										
7390	2746	4644	15	0.5	0.5	11	9	0	0.06	0.34
7632	3071	4562	15	0.5	0.6	11	8	0	0.06	0.37
8060	3160	4901	15	0.5	0.8	14	10	0	0.06	0.42
7349	2520	4830	15	0.6	0.5	13	10	0	0.09	0.34
7542	2713	4830	15	0.5	0.6	13	10	0	0.09	0.37
7922	2995	4927	15	0.5	0.5	13	11	0	0.09	0.42
6981	1689	5292	15	0.7	0.5	0	19	0	0.14	0.34
7169	1363	5806	15	0.5	0.7	8	20	0	0.14	0.37
7517	1559	5957	15	0.5	0.6	13	20	0	0.14	0.42
Investment cost reduction of small wind turbine by 50%; battery storage by 50%										
7394	2782	4612	15	0.5	0.5	10	9	0	0.06	0.34
7682	2883	4799	15	0.6	0.7	14	9	0	0.06	0.37
8035	3142	4894	15	0.6	0.5	15	10	0	0.06	0.42
7371	2618	4753	15	0.7	0.5	10	10	0	0.09	0.34
7519	2741	4778	15	0.5	0.5	12	10	0	0.09	0.37
7973	3188	4785	15	0.5	0.7	11	10	0	0.09	0.42
7045	1435	5610	15	0.5	1.3	2	20	0	0.14	0.34
7142	1376	5766	15	0.5	0.5	11	19	0	0.14	0.37
7504	1630	5874	15	0.5	0.5	11	20	0	0.14	0.42

Table A8. Optimized dimensioning and economic efficiency of the energy supply system of a single building for electricity price and investment cost scenarios. Montreal site.

Total Cost [EUR/a]	Energy Cost [EUR/a]	Invest./ Maintenance [EUR/a]	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	El. Marketing Price [EUR/kWh]	El. Purchase Price [EUR/kWh]
Investment Cost Reduction of Small Wind Turbine by 25%; Battery Storage by 25%										
7851	2493	5357	15	0.6	0.5	2	9	3	0.06	0.34
8015	2222	5793	15	0.5	0.6	7	10	3	0.06	0.37
8317	2430	5886	15	0.5	0.5	9	10	3	0.06	0.42
7577	1829	5748	15	0.5	0.5	3	12	3	0.09	0.34
7830	1342	6488	15	0.6	0.5	7	16	3	0.09	0.37
8103	1310	6793	15	0.5	0.5	11	17	3	0.09	0.42
6811	531	6280	15	0.5	0.7	0	19	3	0.14	0.34
7081	564	6518	15	0.6	0.7	2	19	3	0.14	0.37
7499	556	6943	15	0.8	0.7	6	20	3	0.14	0.42
Investment cost reduction of small wind turbine by 50%; battery storage by 25%										
7502	2298	5204	15	0.5	0.6	3	10	3	0.06	0.34
7703	2295	5408	15	0.6	0.5	6	10	3	0.06	0.37
8001	2175	5826	15	0.5	0.5	12	11	3	0.06	0.42
7253	1791	5462	15	0.5	0.5	2	13	3	0.09	0.34
7544	1689	5855	15	0.8	0.5	7	13	3	0.09	0.37
7841	1427	6414	15	0.5	0.8	11	16	3	0.09	0.42
6431	411	6020	15	0.5	0.5	0	20	3	0.14	0.34
6660	348	6312	15	0.5	0.5	3	20	3	0.14	0.37
7342	685	6657	16	0.5	0.5	6	19	3	0.14	0.42

Table A8. *Cont.*

Total Cost [EUR/a]	Energy Cost [EUR/a]	Invest./ Maintenance [EUR/a]	P_{th} HP [kW]	$V_{storage}$ DHW [m^3]	$V_{storage}$ Room [m^3]	C_{batt} [kWh]	P_{el} PV [kWp]	P_{el} Wind [kW]	El. Marketing Price [EUR/kWh]	El. Purchase Price [EUR/kWh]
Investment cost reduction of small wind turbine by 25%; battery storage by 50%										
7621	1804	5818	15	0.6	0.5	13	10	3	0.06	0.34
7874	1861	6013	15	0.9	0.6	13	11	3	0.06	0.37
8141	2285	5856	15	0.6	0.7	13	10	3	0.06	0.42
7439	1153	6287	15	0.6	0.5	13	14	3	0.09	0.34
7539	982	6557	15	0.5	0.5	15	16	3	0.09	0.37
7813	1116	6697	15	0.5	0.5	16	17	3	0.09	0.42
6688	−67	6755	15	0.5	0.5	8	20	3	0.14	0.34
6885	−16	6901	15	0.5	0.7	11	20	3	0.14	0.37
8733	632	8101	18	0.5	0.6	6	17	7	0.14	0.42
Investment cost reduction of small wind turbine by 50%; battery storage by 50%										
7242	1805	5437	15	0.5	0.5	12	10	3	0.06	0.34
7453	2034	5418	15	0.5	0.6	14	9	3	0.06	0.37
7713	2063	5650	15	0.5	0.5	15	11	3	0.06	0.42
7063	1275	5789	15	0.5	0.5	12	13	3	0.09	0.34
7216	1117	6099	15	0.5	0.5	11	16	3	0.09	0.37
7528	1141	6387	15	0.5	0.6	16	17	3	0.09	0.42
6397	−10	6408	15	0.5	0.6	7	20	3	0.14	0.34
6511	−21	6532	15	0.5	0.5	11	20	3	0.14	0.37
6803	251	6552	15	0.5	0.5	15	19	3	0.14	0.42

References

1. Statistisches Bundesamt. Stromerzeugung 2022, 2023. Available online: https://www.destatis.de/DE/Presse/Pressemitteilungen/2023/03/PD23_090_43312.html (accessed on 27 June 2023).
2. Bundesverband für WindEnergie BWE e.V. Windenergie in Deutschland—Zahlen und Fakten, 2020. Available online: https://www.wind-energie.de/themen/zahlen-und-fakten/deutschland/ (accessed on 15 November 2023) .
3. Gehling, M. *Installierte Leistung, Stromerzeugung und Marktentwicklung von Kleinwindanlagen in Deutschland*; Technical Report; Ingenieurbüro für Erneuerbare Energien: Leipzig, Germany, 2019.
4. Wagh, S.; Walke, T. Review on Wind-Solar Hybrid Power System. *Int. J. Res. Sci. Eng.* **2017**, *3*, 71–76.
5. Acatech. *Wie kann der Ausbau von Photovoltaik und Windenergie Beschleunigt Werden? Stellungnahme*; Technical Report; Leopoldina Akademienunion: Schweinfurt, Germany, 2022.
6. Brennenstuhl, M.; Lust, D.; Boch, P.; Yadack, M.; Eicker, U. The Potential of Small Wind Turbine Integration in Residential Buildings Complementing PV and Heat Pump Operation. *ISEC Conf. Proc. Renew. Heat. Cool. Integr. Urban Ind. Energy Syst.* **2018**, *1*, 331–339.
7. *Absatzzahlen und Marktanteile*; Bundesverband WWärmepumpe (BWP) e. V.: Berlin, Germany, 2023.
8. *Anteil der Elektroautos am Bestand der Personenkraftwagen in Deutschland von 2018 bis 2020 und Prognose bis 2030*; Statista GmbH: Hamburg, Germany, 2022.
9. Ahmed, N.A.; Miyatake, M.; Al-Othman, A.K. Power fluctuations suppression of stand-alone hybrid generation combining solar photovoltaic/wind turbine and fuel cell systems. *Energy Convers. Manag.* **2008**, *49*, 2711–2719. [CrossRef]
10. Mohammadi, S.; Soleymani, S.; Mozafari, B. Scenario-based stochastic operation management of MicroGrid including Wind, Photovoltaic, Micro-Turbine, Fuel Cell and Energy Storage Devices. *Int. J. Electr. Power Energy Syst.* **2014**, *54*, 525–535. [CrossRef]
11. Niknam, T.; Golestaneh, F.; Shafiei, M. Probabilistic energy management of a renewable microgrid with hydrogen storage using self-adaptive charge search algorithm. *Energy* **2013**, *49*, 252–267. [CrossRef]
12. Sichilalu, S.; Tazvinga, H.; Xia, X. Optimal control of a fuel cell/wind/PV/grid hybrid system with thermal heat pump load. *Sol. Energy* **2016**, *135*, 59–69. [CrossRef]
13. Kaabeche, A.; Belhamel, M.; Ibtiouen, R. Techno-economic valuation and optimization of integrated photovoltaic/wind energy conversion system. *Sol. Energy* **2011**, *85*, 2407–2420. [CrossRef]
14. Arabali, A.; Ghofrani, M.; Etezadi-Amoli, M.; Fadali, M.S.; Baghzouz, Y. Genetic-algorithm-based optimization approach for energy management. *IEEE Trans. Power Deliv.* **2013**, *28*, 162–170. [CrossRef]

15. Mazzeo, D.; Matera, N.; De Luca, P.; Baglivo, C.; Congedo, P.M.; Oliveti, G. A literature review and statistical analysis of photovoltaic-wind hybrid renewable system research by considering the most relevant 550 articles: An upgradable matrix literature database. *J. Clean. Prod.* **2021**, *295*, 126070. [CrossRef]
16. Grieser, B.; Sunak, Y.; Madlener, R. Economics of small wind turbines in urban settings: An empirical investigation for Germany. *Renew. Energy* **2015**, *78*, 334–350. [CrossRef]
17. Rieck, J.; Taube, L.; Behrendt, F. Feasibility analysis of a heat pump powered by wind turbines and PV-Applications for detached houses in Germany. *Renew. Energy* **2020**, *162*, 1104–1112. [CrossRef]
18. Weida, S.; Kumar, S.; Madlener, R. Financial viability of grid-connected solar PV and wind power systems in Germany. *Energy Procedia* **2016**, *106*, 35–45. [CrossRef]
19. Weiler, V.; Lust, D.; Brennenstuhl, M.; Brassel, K.H.; Duminil, E.; Eicker, U. Automatic dimensioning of energy system components for building cluster simulation. *Appl. Energy* **2022**, *313*, 118651. [CrossRef]
20. Mayer, M.J.; Szilágyi, A.; Gróf, G. Environmental and economic multi-objective optimization of a household level hybrid renewable energy system by genetic algorithm. *Appl. Energy* **2020**, *269*, 115058. [CrossRef]
21. Ko, M.J.; Kim, Y.S.; Chung, M.H.; Jeon, H.C. Multi-objective optimization design for a hybrid energy system using the genetic algorithm. *Energies* **2015**, *8*, 2924–2949. [CrossRef]
22. Koutroulis, E.; Kolokotsa, D.; Potirakis, A.; Kalaitzakis, K. Methodology for optimal sizing of stand-alone photovoltaic/wind-generator systems using genetic algorithms. *Sol. Energy* **2006**, *80*, 1072–1088. [CrossRef]
23. Zhang, Y.; Lundblad, A.; Campana, P.E.; Yan, J. Comparative Study of Battery Storage and Hydrogen Storage to Increase Photovoltaic Self-sufficiency in a Residential Building of Sweden. *Energy Procedia* **2016**, *103*, 268–273. [CrossRef]
24. Bee, E.; Prada, A.; Baggio, P. Optimization of Air Source Heat Pump Systems over the Heating Season through the Use of Renewable Energy Sources. In Proceedings of the International High Performance Buildings Conference Proceedings, West Lafayette, IN, USA, 11–14 July 2016.
25. Bernal-Agustín, J.L.; Dufo-López, R. Efficient design of hybrid renewable energy systems using evolutionary algorithms. *Energy Convers. Manag.* **2009**, *50*, 479–489. [CrossRef]
26. Xu, X.; Hu, W.; Cao, D.; Huang, Q.; Chen, C.; Chen, Z. Optimized sizing of a standalone PV-wind-hydropower station with pumped-storage installation hybrid energy system. *Renew. Energy* **2020**, *147*, 1418–1431. [CrossRef]
27. Brennenstuhl, M.; Lust, D.; Pietruschka, D.; Schneider, D. Demand Side Management Based Power-to-Heat and Power-to-Gas Optimization Strategies for PV and Wind Self-Consumption in a Residential Building Cluster. *Energies* **2021**, *14*, 6712. [CrossRef]
28. Rosa, M.D.; Brennenstuhl, M.; Cabrera, C.A.; Eicker, U.; Finn, D.P. An Iterative Methodology for Model Complexity Reduction in Residential Building Simulation. *Energies* **2019**, *12*, 2448. [CrossRef]
29. Brennenstuhl, M.; Zeh, R.; Otto, R.; Pesch, R.; Stockinger, V.; Pietruschka, D. Report on a Plus-Energy District with Low-Temperature DHC Network, Novel Agrothermal Heat Source, and Applied Demand Response. *Appl. Sci.* **2019**, *9*, 5059. [CrossRef]
30. Krien, U.; Schönfeldt, P.; Launer, J.; Hilpert, S.; Kaldemeyer, C.; Pleßmann, G. oemof.solph—A model generator for linear and mixed-integer linear optimisation of energy systems. *Softw. Impacts* **2020**, *6*, 100028. [CrossRef]
31. Emmi, G.; Zarrella, A.; De Carli, M.; Galgaro, A. Solar assisted ground source heat pump in cold climates. *Energy Procedia* **2015**, *82*, 623–629. [CrossRef]
32. Government of Canada. Residential Space Heating System Stock Share, 2021. Available online: https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=HB&sector=res&juris=00&rn=13&year=2021&page=0#sources (accessed on 16 March 2025).
33. DWD. Windkarten zur Mittleren Windgeschwindigkeit, 2024. Available online: https://www.dwd.de/DE/leistungen/windkarten/ (accessed on 22 November 2024).
34. Deutsches Institut für Normung e.V. *DIN EN 12831 Energetische Bewertung von Gebäuden—Verfahren zur Berechnung der Norm-Heizlast*; Technical Report; DIN: Berlin, Germany, 2017.
35. CEC. Climate Zones of North America. Available online: https://www.cec.org/mapmonday/climate-zones-in-north-america/ (accessed on 12 December 2024).
36. DWD. Open-Data-Server des Deutschen Wetterdienstes, 2022. Available online: https://opendata.dwd.de/ (accessed on 22 October 2022).
37. Brennenstuhl, M.; Harbola, S.; Koukofikis, A.; Padsala, R.; Schaaf, M.; Coors, V.; Voss, U. CFD Simulation and Visualization Based Investigation of Small Wind Turbine Potential: A Case Study "Neuer Stöckach" for Stuttgart. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2021**, 8, 17-24. [CrossRef]
38. ECCC. Data Download for Montréal, 2022. Available online: https://montreal.weatherstats.ca/ (accessed on 22 January 2025)
39. Jüttemann, P. *Kleinwind-Marktreport Ausgabe 2020*, 6th ed.; Patrick Jüttemann: Bad Honnef, Germany, 2019.
40. Verein Deutscher Ingenieure. *VDI 2067—Economic Efficiency of Building Installations: Fundamentals and Economic Calculation*; Technical Report; Verein Deutscher Ingenieure e.V.: Harzgerode, Germany, 2012.

41. Strom-Report. Strompreisentwicklung—Strompreise sinken 2023 wieder, 2023. Available online: https://strom-report.com/strompreise/strompreisentwicklung/ (accessed on 23 May 2023).
42. Buttelmann, M.; Lohmann, B. Optimierung mit Genetischen Algorithmen und eine Anwendung zur Modellreduktion. *At-Autom.* **2004**, *52*, 151–163. [CrossRef]
43. Kleine Büning, H.; Kramer, O.; Ting, C.; Aslan, D. *Genetische Algorithmen*; Technical Report; Universität Paderborn: Paderborn, Germany, 2007.
44. Bundesministerium für Digitales und Verkehr. Deutsches Mobilitätspanel (MOP), 2021. Available online: https://bmdv.bund.de/SharedDocs/DE/Artikel/G/deutsches-mobilitaetspanel.html (accessed on 16 March 2023).
45. Brennenstuhl, M.; Otto, R.; Elangovan, P.K.; Eicker, U. The Potential of Vehicle-to-Home Integration for Residential Prosumers: A Case Study. *Smart Grids Sustain. Energy* **2024**, *9*, 25. [CrossRef]
46. Lehtola, T.A.; Zahedi, A. Electric Vehicle Battery Cell Cycle Aging in Vehicle to Grid Operations: A Review. *IEEE J. Emerg. Sel. Top. Power Electron.* **2021**, *9*, 423–437. [CrossRef]
47. Rodrigues, A.; Machado, D.; Dentinho, T. Electrical Energy Storage Systems Feasibility; the Case of Terceira Island. *Sustainability* **2017**, *9*, 1276. [CrossRef]
48. Fraunhofer ISE. *Photovoltaics Report*; Fraunhofer ISE: Freiburg, Germany, 2024.
49. DNV. *Energy Transition Outlook 2024: A Global and Regional Forecast to 2050*; Technical Report; DNV: Bærum, Norway, 2024.
50. Orangi, S.; Manjong, N.; Clos, D.P.; Usai, L.; Burheim, O.S.; Strømman, A.H. Historical and prospective lithium-ion battery cost trajectories from a bottom-up production modeling perspective. *J. Energy Storage* **2024**, *76*, 109800. [CrossRef]
51. Renugen Limited. Renugen Limited Marketplace, 2022. Available online: https://www.renugen.co.uk/ (accessed on 11 April 2024).
52. Scon-Marketing GmbH. Das sind die Kosten einer Photovoltaikanlage in 2022, 2022. Available online: https://www.solaranlagen-portal.de/photovoltaik/preis-solar-kosten.html/ (accessed on 11 April 2024).
53. PV Magazine Group GmbH & Co. KG. PV Magazine: Speichermarkt in Deutschland auf Wachstumskurs bei Sinkenden Preisen, 2020. Available online: https://www.pv-magazine.de/2020/12/01/speichermarkt-in-deutschland-auf-wachstumskurs-bei-sinkenden-preisen/ (accessed on 11 March 2025).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.