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Research Article

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

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Abstract

In Germany, renewable energy sources play a crucial role in electricity generation, with wind and photovoltaic (PV) leading the way. In 2022, large wind turbines contributed 24.1% of the electricity generated, while PV accounted for 10.6%. Contrary, small wind power holds a marginal share of less than 0.01%. 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 and transport could create new opportunities. Within this work a residential energy supply system consisting of small wind turbine, PV, heat pump, battery storage, and electric vehicle was dimensioned for different sites in Germany and Canada based on detailed simulation models and genetic algorithms. This was carried out for various economic framework conditions. Results indicate that with electricity purchase costs above 0.42 €/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

1 Introduction

Sector coupling and load management are crucial elements to reach climate neutrality. Today in Germany most of the Renewable Energy Sources (RES) are converted within the domain of the energy sector, thus effective load management becomes important 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 RES 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 bio gas 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 marked 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

In terms of the combination of PV, small wind turbine and energy storage (battery as well as chemical storage), research has so far focused on the optimization of hybrid power generation [9] as well as optimized microgrid operation [10], [11]. Sector coupling based on power-to-heat applications is rarely considered for this particular system combination. Sichilalu et al. [12] studied a system with grid-connected PV, small wind turbine and fuel cell in South Africa, but do not consider the thermal behavior of the building. In [13], an optimization model is developed for a hybrid system of PV, 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 PV 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.

It can be seen that most of the studies do not represent the dynamic behavior of the building. Thus, an increase in flexibility due to overheating or undercooling and the related rebound effect cannot be considered. In addition, no conclusions are drawn specifically for the German region and the parallel operation of PV and small wind turbine with regard to the local climatic and economic conditions.

1.2 Optimized Dimensioning of HVAC Systems

In research, metaheuristic optimization approaches, such as Evolutionary Algorithms (EA) and in particular GA 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 [15]. Specifically for hybrid systems, research has investigated the application of GA for a wide variety of use cases. For example, Mayer et al. [16] use a GA to optimize a hybrid power system consisting of PV, 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 full cost and environmental impact in terms of CO_2 emissions. Ko et al. [17] determine the optimal dimensioning of a system consisting of PV, 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 er al. [18] use GA to find the optimal dimensioning of photovoltaic and small wind turbine to supply a household. Zhang et al. [19] apply a GA to a residential PV, battery storage, and hydrogen storage system to increase self-sufficiency and reduce investment costs. Only the electrical and not the thermal side of the system is considered. Bee et al. [20] use a GA to determine the optimal dimensioning of a system consisting of a heat pump, PV, thermal buffer storage, and battery storage. Bernal-Agustin et al. [21] determine the optimal parameters for an EA to dimension a complex system of PV, small wind turbine, diesel generator, electrolyzer, fuel cell, and battery storage. Xu et al. [22] dimension a system of wind power, PV and pumped storage using GA, Particle Swarm Optimization (PSO) and Simulated Annealing (SA). It is shown that for this specific use case, PSO gives better results than 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 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.

Therefor within this work a dimensioning of a residential building's individual energy system components (small wind turbine, PV, battery storage, heat pump, thermal buffer storages) 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 (as of 2022) 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 a battery electric vehicles (BEV) 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 €/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 €/MWh would prove sufficient for an economic 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 BEV and bidirectional charging does not positively influence the economic feasibility of the considered scenarios for small wind turbine installations. Nonetheless, under future conditions, 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 [23]. For a more in-depth understanding of the configuration of the local cold district heating grid and of the plus-energy settlement, additional insights can be found in [24].

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

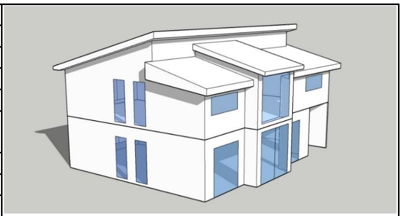


Fig. 1: Building system specifications

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 is used for the sites in Germany. For the Montreal site, a separate profile based on the mean brine temperatures for ground source heat pump operation in Montreal [25] is used.

Table 1: Studied sites. Data sources: a) [26]; b) [27]; c) [28]; d) [25]

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 measurments	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 a small wind turbines [29].

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 [30]. The economic evaluation is calculated in the form of the Equivalent Annual Cost (EAC). These consist of the annual expenditures for the investment, operation, and maintenance of the various system components. The EAC are calculated according to the following equation 1:

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

Table 2: Mean measured annual values of the sites

	$\overline{\mathbf{V}}_{\mathbf{wind}}$ **2019** **[m/s]**	$\overline{\mathbf{V}}_{\mathbf{wind}}$ **2010 - 2020** **[m/s]**	$\overline{\mathbf{\Theta}}_{\mathbf{amb}}$ **2019** **[°C]**	$\overline{\mathbf{\Theta}}_{\mathbf{amb}}$ **2010 - 2020** **[°C]**	$\overline{\mathbf{G}}_{\mathbf{oh}}$ **2019** **[W/m²]**	$\overline{\mathbf{G}}_{\mathbf{oh}}$ **2010 - 2020** **[W/m²]**
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

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 PV 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, the maintenance costs as well as the assumed

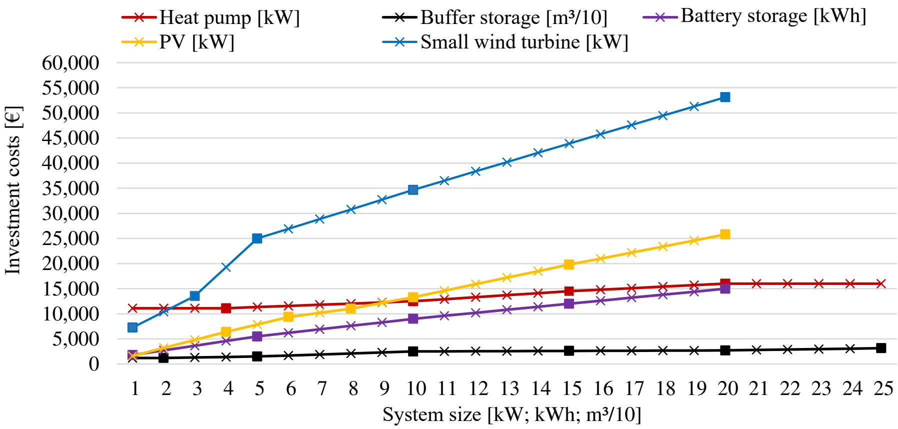


Fig. 2: Interpolated investement costs depending on the system size of the considered system components

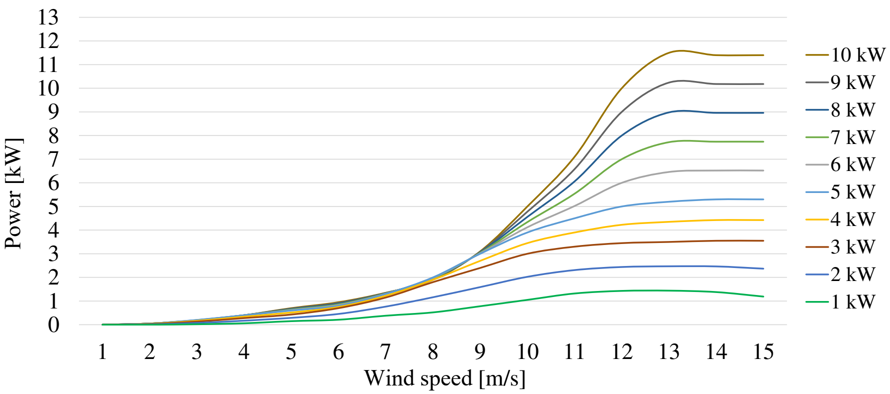


Fig. 3: Interpolated power curves depnding on the wind speed of considered small wind turbines power rating

lifetime are presented in the Appendix 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 are 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 €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 €/kWh for a size up to 10 kWP, and 0.0634 €/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 €/kWh and the electricity purchase price to be 0.34 €/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 (as of May 2023) and according to [31] household prices for new customers are now back to an average of €0.32/kWh, whereas for existing customers they are €0.44/kWh with a downward trend.

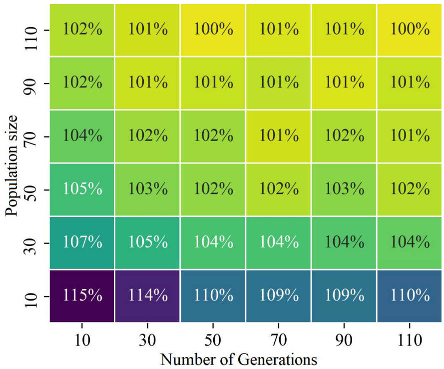
3 Results

3.1 Optimal Parameters for Genetic Algorithms

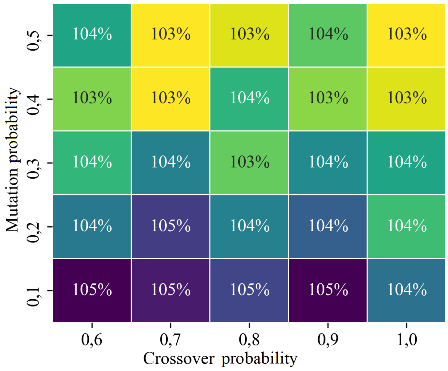
To identify optimal parameters for the utilized genetic algorithm application, aming to find the right balance between computational efficiency and proximity to a global optimum, an iterative study was carried out as outlined in [15]. This involved a incremental iteration in which the number of generations 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 [32], [33]. 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 Figures 4a and 4b. 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 of 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. [15]



(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

Fig. 4: Parameter variation of a genetic algorithm for optimized dimensioning. Own representation, already published in [15]

- 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

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.

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 in a very small size (1 kWh - 2 kWh). The size of the heating buffer storage is moderate at 0.5 m^3 - 0.8 m^3. The PV system is sized to between 4 kWp - 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 current framework conditions. The assumption here is that the applied 80 kWh vehicle battery will be used between 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

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	$\mathbf{P_{th}}$ HP **[kW]**	$\mathbf{V_{storage}}$ DHW **[m³]**	$\mathbf{V_{storage}}$ Room **[m³]**	$\mathbf{C_{batt}}$ **[kWh]**	$\mathbf{P_{el}}$ PV **[kWp]**	$\mathbf{P_{el}}$ wind **[kW]**	**Total costs [€/a]**	**Energy costs [€/a]**	**Invest. and maintenance [€/a]**
Aachen	15	0.5	0.7	1	4	3	7,084	1,925	5,159
Braunlage	15	0.5	0.8	0	9	0	7,922	3,732	4,190
Greifswald	15	0.5	0.6	0	4	0	7,430	3,799	3,631
Potsdam	15	0.7	0.6	0	5	0	7,428	3,625	3,803
Stuttgart	15	0.6	0.5	0	8	0	6,868	2,819	4,049
Wüstenrot	15	0.6	0.6	0	8	0	7,541	3,472	4,069
Montreal	15	0.7	0.6	2	9	3	8,316	2,517	5,798

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 secondary car, which has longer parking hours at home at the charging port.

The results for the first driving profile, which generally always 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.

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

Location	$\mathbf{P_{th}}$ HP **[kW]**	$\mathbf{V_{storage}}$ DHW **[m³]**	$\mathbf{V_{storage}}$ Room **[m³]**	$\mathbf{C_{batt}}$ **[kWh]**	$\mathbf{P_{el}}$ PV **[kWp]**	$\mathbf{P_{el}}$ wind **[kW]**	**Total costs [€/a]**	**Energy costs [€/a]**	**Invest. and maintenance [€/a]**
Aachen	15	0.5	0.5	16	0	3	7,199	2,847	4,351
Braunlage	15	0.5	0.6	16	4	0	7,912	4,282	3,631
Greifswald	15	0.5	0.5	16	4	0	7,502	3,891	3,611
Potsdam	15	0.8	0.6	16	9	0	7,490	3,281	4,210
Stuttgart	15	0.7	0.5	16	9	0	6,995	2,824	4,171
Wüstenrot	15	0.6	0.5	16	4	0	7,584	3,953	3,631
Montreal	15	0.7	0.7	16	10	0	8,268	3,957	4,312

It can be seen that for the driving profile first car, commuting to work 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 BEV 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 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 €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 BEV, despite the additional purchase of 2,410.7 kWh of electricity for the BEV, because vehicle-to-home use can increase self electricity consumption without additional investment costs.

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 second car, energy and investment costs as of 2022)

Location	$\mathbf{P_{th}}$ HP **[kW]**	$\mathbf{V_{storage}}$ DHW $\mathbf{[m^8]}$	$\mathbf{V_{storage}}$ Room $\mathbf{[m^8]}$	$\mathbf{C_{batt}}$ **[kWh]**	$\mathbf{P_{el}}$ PV **[kWp]**	$\mathbf{P_{el}}$ wind **[kW]**	**Total costs [€/a]**	**Energy costs [€/a]**	**Invest. and maintenance [€/a]**
Aachen	16	0.5	0.5	16	8	3	6,856	1,395	5,462
Braunlage	15	0.6	0.7	16	9	0	7,700	3,510	4,190
Greifswald	15	0.7	0.5	16	10	0	7,261	2,989	4,273
Potsdam	15	0.7	0.5	16	8	0	7,152	3,084	4,069
Stuttgart	15	0.5	0.5	16	11	0	6,556	2,205	4,351
Wüstenrot	15	0.7	0.6	16	10	0	7,367	3,075	4,292
Montreal	15	0.6	0.6	16	12	0	7,889	3,382	4,507

Regarding the second car driving profile it can be seen that 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 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 driving profile second car, despite the 1,366.3 kWh increase in demand due to the BEV.

However, this economic evaluations do not include any possible damage to the vehicle battery due to additional cycles. According to a previously carried out study this would be between €175.5 and €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 would possibly be reached sooner despite vehicle-to-home operation, rather than the vehicle battery falling below 80% in capacity [34].

3.4 Future Framework Conditions

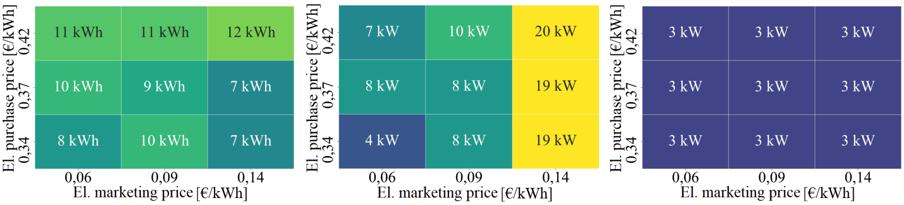
In the following, the system components are dimensioned for the different locations with respect to increasing electricity purchase and electricity marketing prices and decreasing capital costs. Thereby the system components are each dimensioned for various cost combinations. These are an electricity purchase price of 0.34 €/kWh, of 0.37 €/kWh and of 0.42 €/kWh; an electricity marketing price of 0.06 €/kWh, of 0.09 €/kWh and of 0.14 €/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, since on the one hand no significant cost reductions are to be expected for these technologies, due to their market maturity and the corresponding large-scale production, and on the other hand the calculation time of the dimensioning would increase eightfold.

Aachen, Germany

Figures 5a, 5b, 5c 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 small wind turbine and battery storage compared to today's prices (as of 2022). In Figures 6a, 6b, 6c this is done for an investment cost reduction of 50%. Thereby green and more yellow colors indicate, that a large system is more economic. 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 in Table A2.

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

Fig. 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.



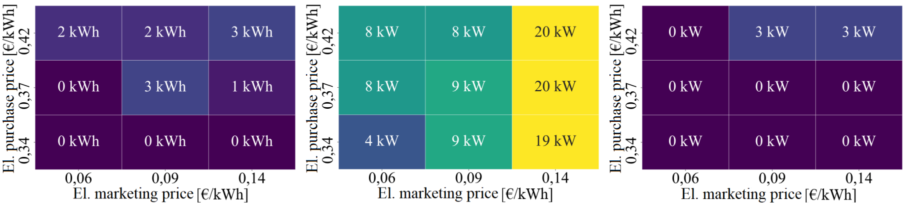
(a) Optimal battery storage size (b) Optimal PV system size (c) Optimal wind turbine size

Fig. 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 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 25% investment cost reduction. In the most favorable case (electricity purchase price of 0.42 €/kWh; electricity marketing price of 0.06 €/kWh), a battery storage size of 8 kWh would be the most economical. In the worst case (electricity purchase price of 0.34 €/kWh; electricity marketing price of 0.14 €/kWh), the installation of a battery storage would not make sense. With 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 €/kWh, a PV system size between 19 kWp - 20 kWp would be the most economical. In the worst case (electricity purchase price of 0.34 €/kWh; electricity marketing price of 0.06 €/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.

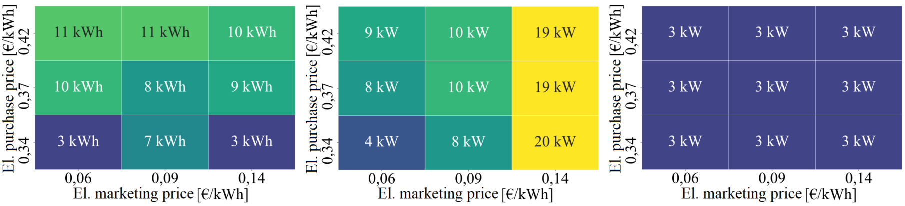
Braunlage, Germany

Figures 7a, 7b, 7c 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 small wind turbine and battery storage compared to today's prices (as of 2022). In Figures 8a, 8b, 8c this is done for an investment cost reduction of 50%. Thereby green and more yellow colors indicate, that a large system is more economic. 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 in Table A3.



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

Fig. 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



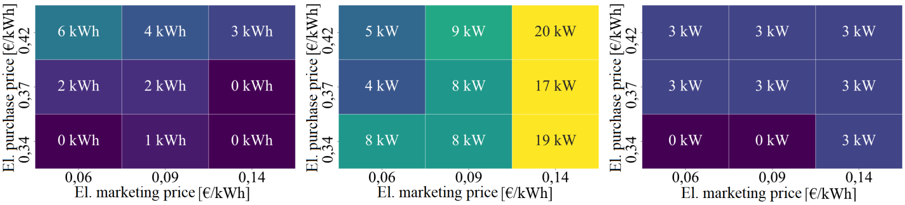
(a) Optimal battery storage size (b) Optimal PV system size (c) Optimal wind turbine size

Fig. 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 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 €/kWh and an electricity marketing price of 0.09 €/kWh or 0.14 €/kWh. For an investment cost reduction of 50% the operation of a small wind turbine would make sense for all electricity purchase and electricity marketing price constellations. The best small wind turbine size would be 3 kW. The optimal battery storage size at 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 €/kWh; electricity marketing price of 0.14 €/kWh), a battery storage size of 8 kWh would be the most economical. At an electricity purchase price of 0.34 €/kWh, a battery storage system does not make sense for all electricity marketing prices. With 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 €/kWh, storage sizes of 3 kWh - 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 €/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 of the battery storage by 25%, the most economic small wind turbine size would be the same as for the variant of investment cost reduction of 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 €/kWh, a PV system size between 19 kWp - 20 kWp would be the most economical. In the worst case (electricity purchase price of 0.34 €/kWh; electricity marketing price of 0.06 €/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.

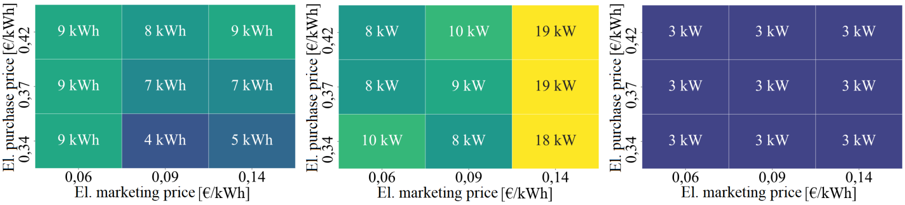
Greifswald, Germany

Figures 9a, 9b, 9c 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 small wind turbine and battery storage compared to today's prices (as of 2022). In Figures 10a, 10b, 10c this is done for an investment cost reduction of 50%. Thereby green and more yellow colors indicate, that a large system is more economic. 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 in Table A4.



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

Fig. 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



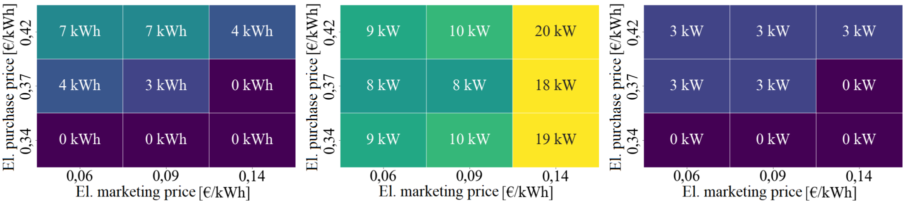
(a) Optimal battery storage size (b) Optimal PV system size (c) Optimal wind turbine size

Fig. 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 €/kWh and an electricity marketing price of 0.06 €/kWh or 0.09 €/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 purchase and electricity marketing price constellations. The best small wind turbine size would also be 3 kW. The optimal battery storage size at 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 €/kWh; electricity marketing price of 0.06 €/kWh), a battery storage size of 6 kWh would be the most economical. At an electricity purchase price of 0.34 €/kWh and an electricity marketing price of 0.06 €/kWh and 0.14 €/kWh, as well as at an electricity purchase price of 0.37 €/kWh and an electricity marketing price of 0.14 €/kWh, a battery storage system does not make sense. With 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 investment cost reduction of 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 €/kWh and an electricity purchase price of 0.37 €/kWh or 0.42 €/kWh. In this case, the reduction of 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 €/kWh, a PV system size between 17 kWp - 20 kWp would be the most economical. The optimal heat pump size is consistently 15 kW, 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.

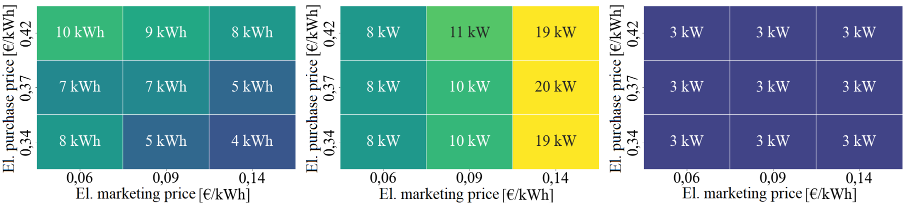
Potsdam, Germany

Figures 11a, 11b, 11c 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 small wind turbine and battery storage compared to today's prices (as of 2022). In Figures 12a, 12b, 12c this is done for an investment cost reduction of 50%. Thereby green and more yellow colors indicate, that a large system is more economic. 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 in Table A5.



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

Fig. 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



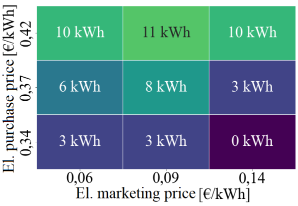
(a) Optimal battery storage size (b) Optimal PV system size (c) Optimal wind turbine size

Fig. 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

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 €/kWh and an electricity purchase price of 0.37 €/kWh in combination with an electricity marketing price of 0.14 €/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 purchase and electricity marketing price constellations. The best small wind turbine size would also be 3 kW. The optimal battery storage size at 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 €/kWh; electricity marketing price of 0.06 €/kWh), a battery storage size of 7 kWh would be the most economical. With 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 of 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 €/kWh, a PV system size between 18 kWp - 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.

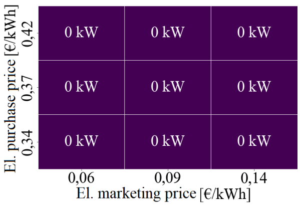
Stuttgart, Germany

Figures 13a, 13b, 13c 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 small wind turbine and battery storage compared to today's prices (as of 2022). In Figures 14a, 14b, 14c this is done for an investment cost reduction of 50%. Thereby green and more yellow colors indicate, that a large system is more economic. 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 in Table A6.



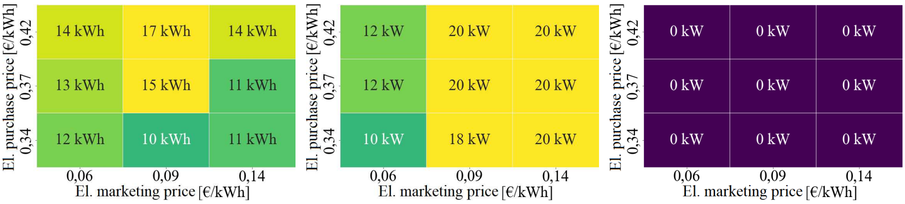
(a) Optimal battery storage size

(b) Optimal PV system size



(c) Optimal wind turbine size

Fig. 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



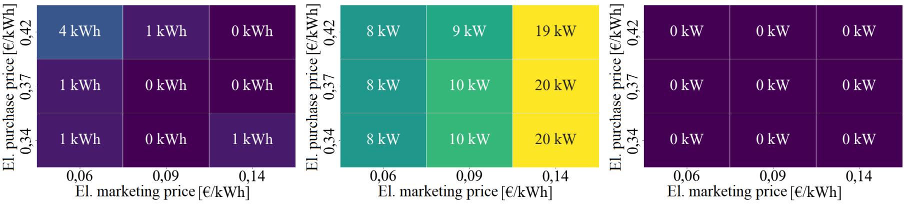
(a) Optimal battery storage size (b) Optimal PV system size (c) Optimal wind turbine size

Fig. 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

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 it was already the case under current framework conditions shown in Table 3. At 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 a electricity purchase price of 0.34 €/kWh and a electricity marketing price of 0.14 €/kWh. For the other constellations, the most reasonable battery storage size varies between 3 kWh and 11 kWh. With 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 PV system size. In the most favorable case of an electricity marketing price of 0.14 €/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.

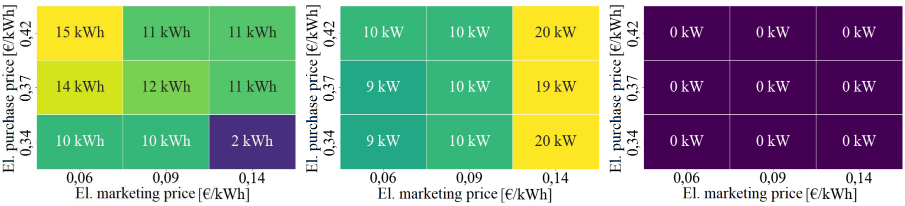
Wüstenrot, Germany

Figures 15a, 15b, 15c 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 small wind turbine and battery storage by 25% compared to today's prices (as of 2022). In Figures 16a, 16b, 16c this is done 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 the Appendix in Table A7.



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

Fig. 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



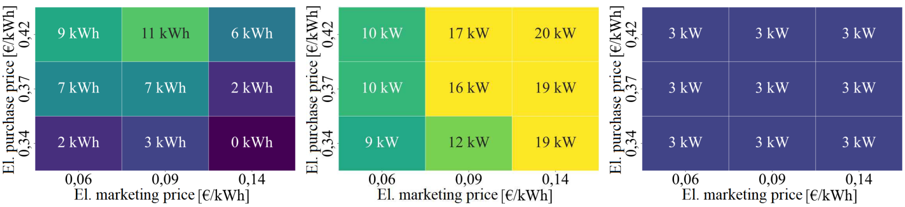
(a) Optimal battery storage size (b) Optimal PV system size (c) Optimal wind turbine size

Fig. 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 it 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 €/kWh and an electricity marketing price of 0.06 €/kWh, the battery storage is dimensioned with 4 kWh. A 50% investment cost reduction results in the best case (electricity purchase price of 0.34 €/kWh and an electricity marketing price of 0.14 €/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 PV system size. In the most favorable case of an electricity marketing price of 0.14 €/kWh, a PV system size of 19 kWp - 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.

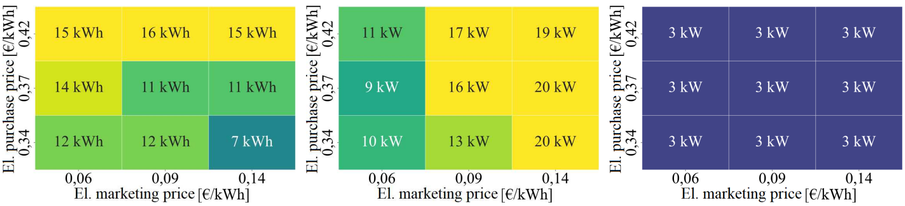
Montreal, Canada

Figures 17a, 17b, 17c 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 small wind turbine and battery storage compared to today's prices (as of 2022). In Figures 18a, 18b, 18c this is done for an investment cost reduction of 50%. Thereby green and more yellow colors indicate, that a large system is more economic. 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 in Table A8.



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

Fig. 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

Fig. 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 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 €/kWh; electricity marketing price of 0.09 €/kWh), a battery storage size of 11 kWh would be the most economical. With an electricity purchase price of 0.34 €/kWh and an electricity marketing price of 0.14 €/kWh, a battery storage system does not make sense. With 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 €/kWh, a PV system size between 19 kWp - 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 where dimensioned for different scenarios for different locations with and without integration of a BEV using vehicle-to-home under current framework conditions. Under future framework conditions, different electricity purchase and electricity marketing prices were included in the dimensioning with a gradual reduction of the investment costs of the small wind turbine and battery storage.

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 of a very small size (1 kWh - 2 kWh). The size of the heating buffer storage is normal at 0.5 m^3 - 0.8 m^3. The PV system is sized between 4 kWp - 9 kWp depending on the irradiation of the location.

In Figure 19, the mean value of the dimensioned system size of 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 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 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 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

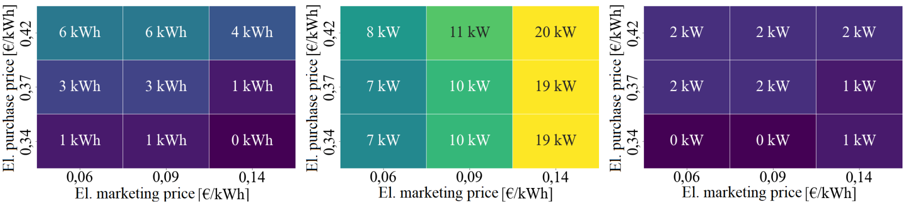
Fig. 19: Optimal system component sizes for a single-family house, current state (as of 2022) without and with vehicle-to-home use, mean values across all locations studied in Germany

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 2,410.7 kWh (first car) or 1,366.3 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 €175.5 and €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 would possibly be reached earlier despite vehicle-to-home operation, rather than the vehicle battery falling below 80% in capacity [34].

Future Framework Conditions

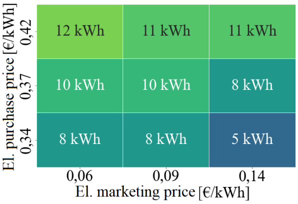
With regard to the future scenarios examined, it should be noted that no investment cost reductions were assumed for the PV system, since the prices here have already reached a very low level, whereas larger cost reductions can be assumed for battery storage and possibly also for small wind turbine due 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 for 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 small wind turbines of smaller size are preferred, since their performance values differ little at low wind speeds (2.5 m/s - 4 m/s) (see Figure 3), whereas the costs increase disproportionately in comparison. The interaction of costs (see Figure 2 and characteristics (see Figure 3) also explains why the dimensioning of 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 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%.

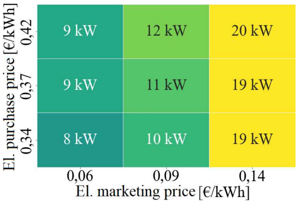


(a) Optimal battery storage size (b) Optimal PV system size (c) Optimal wind turbine size

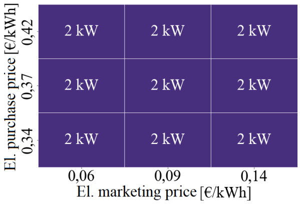
Fig. 20: Optimal system component sizes as a function of the electricity purchase and marketing price with an investment cost reduction of 25% for small wind turbine and battery storage, average values across all locations investigated in Germany



(a) Optimal battery storage size



(b) Optimal PV system size



(c) Optimal wind turbine size

Fig. 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

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 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.

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 of the investment costs also has a noticeable effect, whereby at higher electricity purchase prices of $\geq$ 0,37 €/kWh already an investment cost reduction of 25% 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 of 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 €/kWh, battery storage sizes of 5 kWh - 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 also shows 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.

Conclusions

Our observations indicate that higher electricity procurement costs, specifically those exceeding 0.42 €/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 €/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 (BEV) 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.

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5 Declarations

Ethical Approval
Not applicable.

Competing interests
No conflict of interest / competing interests exist regarding this work.

Authors' 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 was carried out by M.B. U.E. revised this work critically for important intellectual content.

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Availability of data and materials
The underlying data can be made available on demand.

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Appendix A Detailed Dimensioning Results

Table A1: Size-specific investment costs of different energy supply systems. Cost sources: a) [35] small wind turbine type Aeolos-V incl. 43% costs for foundation, mast and installation; b) [36] incl. inverter and installation; c) [37]; own research of current trade prices incl. 2.500 € installation costs; e) own research of current trade prices incl. 1.000 € installation costs

Small wind turbine

System size [kW]	**Invest [€]** $^{(a)}$	**Maintenance cost**	**Life span**
1 kW	7.254		
3 kW	13.549		
5 kW	25.000	3,0%	20 years
10 kW	34.658		
20 kW	53.130		

PV system

System size [kW]	**Invest [€]** $^{(b)}$	**Maintenance cost**	**Life span**
4	6,400		
6	9,360		
8	11,040		
10	13,300	2.3%	20 years
15	19,800		
20	25,800		

Battery storage

System size [kW]	**Invest [€]** $^{(c)}$	**Maintenance cost**	**Life span**
0	1,800		
5	5,500		
10	9,000	2.3%	15 years
15	12,000		
20	15,000		

Heat pump

System size [kW]	**Invest [€]** $^{(d)}$	**Maintenance cost**	**Life span**
0	11,100		
4	11,100		
10	12,500	3.5%	20 years
15	14,500		
20	16,000		

Thermal buffer storage

System size [l]	**Invest [€]** $^{(e)}$	**Maintenance cost**	**Life span**
200	1,200		
500	1,500		
1,000	2,500		
1,500	2,600	3.0%	20 years
2,000	2,700		
3,000	3,600		

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 [€/a]	Energy cost [€/a]	Invest./ maintenance [€/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 [€/kWh]	El. purchase price [€/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
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 [€/a]	**Energy cost** [€/a]	**Invest./ maintenance** [€/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** [€/kWh]	**El. purchase price** [€/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
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 [€/a]	Energy cost [€/a]	Invest./ maintenance [€/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 [€/kWh]	El. purchase price [€/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
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 [€/a]	Energy cost [€/a]	Invest./ maintenance [€/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 [€/kWh]	El. purchase price [€/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
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 [€/a]	Energy cost [€/a]	Invest./ maintenance [€/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 [€/kWh]	El. purchase price [€/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
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 [€/a]	Energy cost [€/a]	Invest./maintenance [€/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 [€/kWh]	El. purchase price [€/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
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 [€/a]	Energy cost [€/a]	Invest./ maintenance [€/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 [€/kWh]	El. purchase price [€/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
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