energies

Article

Techno-Economic Analysis of Grid-Connected PV Battery Solutions for Holiday Homes in Sweden

Frank Fiedler * and Joaquin Coll Matas

School of Information and Engineering, Dalarna University, 79188 Falun, Sweden
* Correspondence: ffi@du.se

Abstract: Grid-connected PV battery systems for private homes are becoming increasingly popular in many countries, including Sweden. This study aimed to evaluate the techno-economic feasibility of such distributed, grid-connected PV battery systems for single homes at a Swedish holiday location. It was especially of interest to investigate the impact of demand charges, as they are frequently introduced by utilities in Sweden and are also common in popular winter sport regions. Grid-connected PV battery systems were sized and optimized based on their net present cost. Load patterns, incentives, demand tariff structures and electricity price variation were used to study the sensitivity of the obtained results. Grid-connected residential PV battery systems were found to be equally profitable compared to grid-connected PV systems without batteries when demand charges were applied. When the load profiles had peak loads throughout the whole year and the batteries were large enough sized to shave many peaks, grid-connected PV battery systems had slightly higher profitability than grid-connected PV systems without batteries. The total savings also depended on the actual rate of demand charge. The good profitability we found greatly depends on the current state incentives for these systems in the form of tax credits for surplus electricity and investment costs. Removing the tax credit for surplus electricity would reduce the savings generated by a grid-connected PV system without batteries significantly more than for grid-connected PV systems with batteries.

Keywords: residential PV battery systems; grid-connected; demand charges; peak shaving; holiday homes

Citation: Fiedler, F.; Matas, J.C. Techno-Economic Analysis of Grid-Connected PV Battery Solutions for Holiday Homes in Sweden. *Energies* **2022**, *15*, 2838. https://doi.org/10.3390/en15082838

Academic Editor: Luis Hernández-Callejo

Received: 28 February 2022
Accepted: 4 April 2022
Published: 13 April 2022

1. Introduction

The number of grid-connected PV installations in Sweden is increasing rapidly with an average growth rate of about 55% during the last four years [1,2]. Battery storage solutions in combination with a grid-connected PV system are becoming more popular. This development is supported in Sweden by tax incentives that can stand for about 50% of the turnkey cost of a battery installation. Furthermore, the availability of readymade solutions has increased as the market for PV battery systems grows worldwide and has achieved a substantial market share in Germany and a few other European countries. According to the German solar industry association (BSW), by 2020, a total of 272,000 distributed battery storage sites were installed in Germany, with 88,000 of those just installed in 2020 [3]. SolarPower Europe forecast, in a recent study for the European market, a growth from 3 GWh installed storage capacity in 2020 to 12.8 GWh in 2025. The top markets for residential battery storage in Europe are Germany, Italy, the UK, Austria and Switzerland, representing 90% of new residential battery storage installations, where Germany stands for about two-thirds of the installations. The main reason for the strong growth in the German market is the increasing attractiveness of self-consumption, as retail (purchased) electricity is about three times more expensive than the current feed-in tariff for PV electricity [4].

PV battery solutions are marketed and sold today by many installers and wholesalers in Sweden. The sales are driven by interest from private homeowners and their desire to achieve greater self-sufficiency in electricity. There is also strong interest from the utilities in examining if such distributed battery storage can support the grid. In Sweden, the generation and use of electricity are geographically unevenly distributed, with a lot of generation in the north and most demand in the south and the region of Stockholm. Even though Sweden is a net producer of electricity, during the winter months and peak hours, the high demand requires the import of electricity, use of costly production sources or long transport of electricity, resulting in high prices during these periods. These effects are also pronounced in the skiing areas of Sweden. Electricity use peaks during the skiing season in winter and there are high hourly peak loads as many holiday homes are equipped with electrically heated saunas.

Grid-connected PV battery systems for Swedish conditions have already been studied quite intensively. Many of these studies have particularly focused on the sizing of the batteries for PV installations in single-family homes and the operation strategies, often aiming to enhance the level of self-usage of the generated PV electricity [5–7].

Thygesen and Karlsson [8] compared battery storage and thermal storage as ways to enhance the self-usage of PV electricity in a single home heated with a ground-source heat pump. They found that similar PV self-usage levels can be achieved with both types of storage but for a much lower cost if thermal storage is used. Psimopoulos et al. [9] studied control strategies for single a home heated by an exhaust air heat pump, including thermal storage combined with a PV battery storage system. The aim was to minimize the final bought energy and increase the PV self-usage by making the best use of the available storage options.

Heinisch et al. [10] studied the optimal operation of distributed PV battery systems from user and electricity system perspectives. While from the user side, it is most beneficial to maximize self-usage, the avoidance of expensive peak unit generation and curtailment of non-dispatchable power generation make battery operation most interesting from an electricity system perspective.

Battery systems installed with the aim to increase PV self-usage in single-family homes in Sweden were studied by Facsì [11] in 2019. Despite incentives such as tax reductions, these systems were not found cost-effective as the hourly electricity price difference between purchased and exported electricity was found to be too low. This was even the case if the load included electric vehicle (EV) charging, if studied for a single home or a group of single homes, and with more even load patterns considered [12] or a set of multi-family houses [13].

Batteries in PV battery systems can only be economically motivated if the price difference between the electricity required to charge the batteries, when compared to the values of the electricity discharged from the batteries, is enough to cover the storage cost, termed the levelized cost of storage (LCOS). This could be achieved by using the battery for grid services such as primary frequency control [14]. Cost-effectiveness could be also achieved by peak load shaving for households where grid utilities have power demand charges. In Sweden, about 20% of the 150 grid utilities have introduced power demand tariffs and others are considering introducing them [15]. When PV battery systems are used to increase PV self-usage, depending on the sizing and operation strategy, peak PV generation and peak load demands will be reduced. Luthander et al. [16] studied a PV battery system for single homes and groups of single homes, including peak shaving but with a focus on the comparison of how joint or individual metering and join or individual storage affected self-consumption. The peak shaving investigated in this paper was aimed, first, at reducing the peak production of the PV systems by curtailment, to avoid overloading the electrical grid, rather than to reduce peak demand loads. So far, there has been no study in Sweden to investigate the economic feasibility of peak load shaving with distributed battery storage and imposed demand charges. This has been done in Finland [17] and the United States [18] for local and theoretical tariffs, respectively, with promising results. Yet, in neither study was the distributed battery storage combined with a PV system.

The profitability of grid-connected distributed PV battery systems has been one of the major interests of many studies for the German market, where retail electricity prices are among the highest in Europe and residential battery systems are supported by state subsidies. These studies also investigated various sizing aspects, control strategies, storage management and other technical and economical parameters [19–24]. As an overall conclusion from these papers, it can be stated that grid-connected, distributed PV battery systems are in most cases profitable, with a trend of increasing profitability in recent years due to decreasing investment costs and lower revenues from exporting electricity to the grid. PV battery systems have been studied for various load profiles, including electrically charging vehicles, and German boundary conditions [25]. Tariffs with demand charges that do not yet exist in Germany were suggested to meet the future challenges associated with increasing peak loads due to vehicle charging.

Dietrich and Weber [26] found, with the German regulatory and fiscal framework and cost figures from 2017, that profitability is size-dependent and very small systems do not create a return on investment while there is profitability for systems with a PV capacity of more than 6 kW and inverter capacity of 2.5 kW. However, it must be considered that since 2017, prices for both PV and battery equipment have significantly decreased.

In a broad review-based paper, O'Shaughnessy et al. [27] concluded that batteries have the greatest potential to improve the profitability of PV systems when electricity export rates are lower than retail rates and when peak load periods and demand charges do not coincide with the PV output. In our case, all these conditions were apparent even though the gap between export and retail rates is reduced by tax subsidies. We hypothesized that there could be profitability for distributed PV battery systems for holiday homes with demand charges in Sweden.

A study by Foles et al. [28] for various locations in Portugal revealed good profitability of residential PV systems, but no profitability for most PV battery systems. The best values were obtained when there was a bi-hourly electricity tariff where fixed peak periods with higher kWh rates were included.

The profitability of residential, grid-connected PV battery systems was also studied for country-specific boundary conditions in the United States [29], Thailand [30] and Finland [31,32]. While such systems, if optimally sized, are profitable in the US, they are not in Thailand or Finland, mainly due to the low electricity retail rates and high investment costs.

Residential PV battery installations have been investigated in Australia, including consumer tariffs with various demand charges [33]. The authors studied the reduction in purchased electricity and peak demand for many tariffs and system sizes. However, a full economic evaluation, such as NPC calculation or cash flow, was not included.

Li et al. [34] studied the techno-economic performance of the grid-connected residential PV-battery system in Japan. Besides PV self-consumption, peak shaving aspects with a grid perspective were also investigated for the specific grid conditions at Kyushi island, assuming a certain PV penetration rate and battery capacity. The authors observed a change in the demand curve during the afternoon and evening, i.e., when the demand was highest for that location. However, the battery charge control had no active peak demand reduction strategy, meaning this peak reduction was a side effect of enhanced self-consumption, and as there were no demand charges, there was also no economic incentive for active user-demand peak shaving.

This study aimed to answer the following question. What is the optimal sizing of a distributed PV battery system for a typical Swedish holiday home when demand charges are applied, and is such a system economically feasible? As described before, this has not yet been determined in a Swedish context, and the few studies from other countries have focused little on those specific aspects. Demand charges are expected to be implemented by an increasing number of utilities. Holiday homes are current examples where peak loads occur frequently due to the use of electric sauna heaters. However, an increase in electrical vehicles will also lead to higher peak loads in detached houses.

2. Boundary Conditions and Input Data

The research question was approached by modeling and simulating distributed PV battery solutions as realistically as possible, based on real system components and with both technical and economical boundary conditions from real cases in Sweden. As a tool, the simulation software HOMER Grid [35] was used, which allows for detailed modeling of such systems, including all relevant boundary conditions. Furthermore, HOMER Grid is designed for the techno-economic sizing and optimization of renewable energy systems, which are used for the initial sizing of PV battery systems.

2.1. Electricity Usage

This study was based on hourly electricity usage data from four randomly chosen holiday homes in Sälen, a tourist location in one of the mountainous areas in Sweden. All four datasets were for the year 2019, and therefore, not affected by the COVID-19 pandemic. Figure 1 shows the annual and monthly electricity use for the four houses, as well as the highest peak load for each month. It can clearly be seen that most electricity use and the highest peaks occurred during the winter skiing season. The four houses significantly differed in their total annual and monthly loads due to different occupancy patterns. Analysis of the daily electricity usage data indicated that there was, on average, no major differences between weekend and weekdays.

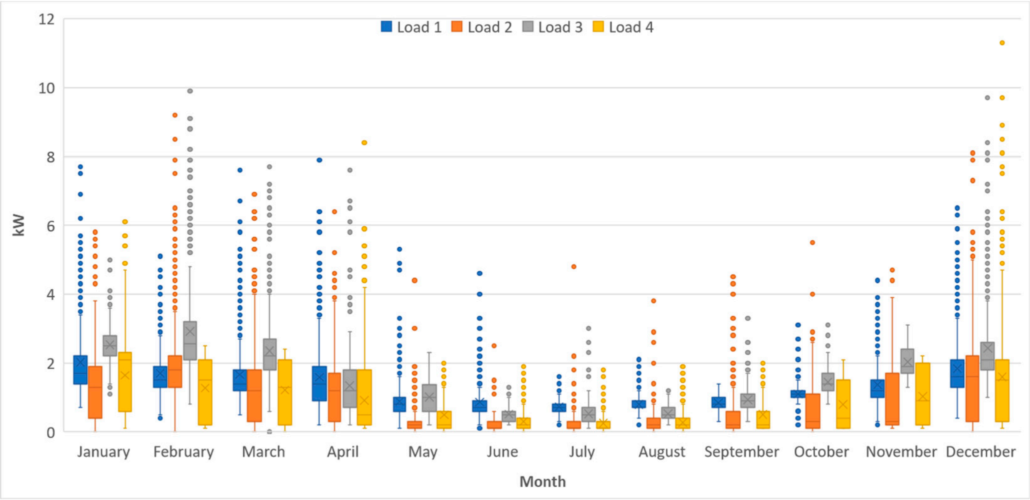

Figure 1. Annual, monthly and peak loads for four holiday homes in Sälen.

Load profiles 1 and 3 had the highest total electricity use, with the highest demand levels and peak loads in winter and early spring. Load profiles 2 and 4 had significantly lower total annual electricity use compared load profiles 1 and 3. The monthly use in both profiles was similar, while the peak values were rather different. Load 2 had peak values over the whole year, while in load 4, high peaks mainly occurred for three months. This difference could be explained by different user behavior and occupancy patterns.

2.2. Solar Radiation Data

No ground-measured solar radiation data are available for the chosen location, Sälen. Existing data sources are based on satellite data and interpolations of ground measurement stations and satellite data. Various data sources were compared and data from the ERA5 Satellite, available through the PVGIS database [36], for 2016 were chosen. The annual horizontal irradiation was 932 kWh/m^2, which was consistent with data from the Swedish Meteorological and Hydrological Institute (SMHI) [37]. Snow soiling losses of 10–25% from November to April were included in the solar radiation modeling. The PV modules in the study were modeled for a tilt angle of 30°, azimuth of 0° and all-year-round ground reflectance of 20%.

2.3. Electricity Prices, Tariffs and Revenues from PV Electricity Sold

In Sweden, electricity users are customers of two utilities, the grid utility and the energy utility. The grid utility charges the consumer for the use of the electrical grid, while the energy utility is a broker for electricity they buy on the market and resell to the customer. Typically, both types of utilities have fixed charges (per year/month) and flexible charges for the electricity (per kWh). Some grid utilities have also introduced demand charges, typically per the maximum or average peak power demand for one month. The electricity prices (per kWh) used in this study were based on the NordPool spot market and used to model the charges from the energy utility, including the typical profit margin. Sweden has four geographical electricity price zones, dividing the country from north to south. NordPool's hourly market prices for 2019 were chosen for zone 3 where Sälen is located.

Several grid utilities were identified as applying demand charges for small customers with a three-phase connection of 16A. For the simulations, the tariffs of two utilities were selected, representing a high demand-charge tariff structure (utility 1) and a more moderate demand-charge tariff structure (utility 2). In addition, as a reference, a third tariff was modeled, representing a typical tariff structure of a utility without demand charges. The tariffs can be seen in Table 1, where utilities 1 and 2 have demand charges but not 3.

Table 1. Tariff structures for the three chosen utilities.

Tariff	Utility 1	Utility 2	Utility 3	Cost Incl. VAT
Demand charge Apr–Oct	75.00	28.41	0	SEK/kW, month
Demand charge Nov–Mar	121.25	28.41 *	0	SEK/kW, month
Annual fee	2050	2131	3590	SEK/year
Variable fee Nov–Mar for weekdays 06–22	0.135	0.075	0.3125	SEK/kWh
Variable fee Nov–Mar for other hours	0.0838	0.075	0.3125	SEK/kWh
Variable fee Apr–Oct	0.0838	0.075	0.3125	SEK/kWh

* On weekdays 6–18, an additional 89.21 SEK/kW is charged.

The total customer electricity price structure further includes taxes and additional fees, such as the general energy tax, VAT and cost of the green electricity certificate. HOMER Grid has comprehensive input options for electricity tariffs, allowing for detailed and accurate modeling of the electricity costs and revenues for PV installations.

Electricity from a residential PV system can be used to reduce the amount of purchased electricity. Typically, PV systems are connected on the consumer side of the electrical meter. Electrical meters are bidirectional and measure both imported and exported electricity. As the electricity output from PV mismatches typical residential electricity use, both on an hourly and seasonal scale, a large share of the generated electricity must be exported. Most utilities buy electricity at the spot market prices, which are much lower than what customers pay, as customer prices include various fees and taxes as described above. This makes residential PV systems in Sweden less profitable, and to compensate for that, the government grants a tax credit of 0.6 SEK for each exported kWh, provided the maximum number of kWh does not exceed the number of kWh of bought electricity within the same year. There is also a total limit on the electricity export of 30,000 kWh for this tax credit [1].

Owners of residential PV installations are also entitled to compensation from the grid utility for the electricity that is fed into the grid. This compensation varies, depending on the grid owner, between 0.02 and 0.10 SEK/kWh. In our model, we used 0.05 SEK/kWh.

Other revenues for selling electricity, such as green electricity certificates and guarantees of origins, were not considered as they give no or very little benefit for small PV installations.

In the simulations, the value of the exported electricity was modeled with the hourly spot market prices for 2019, tax credit of 0.6 SEK per kWh and grid compensation of 0.05 SEK/kWh.

2.4. System Components and Costs

Residential, distributed PV battery systems can be designed in different ways, where batteries are coupled to the system either on the AC or DC side. The most common way is to connect them to the DC side via a so-called hybrid inverter. This is the most common solution on the market and the one that was used in the simulations. For pre-sizing of the systems, cost modeling was based on average turnkey prices for PV installations (without a battery) on single-family houses in Sweden of 12.12 SEK/W plus VAT for sizes between 10 and 20 kW PV [1]. Some of the systems in our simulations were slightly smaller (9 kW) but the same turnkey price was applied. The costs of PV battery systems were modeled with the help of a cost breakdown for a typical PV installation without batteries, as provided in [38]. The higher capital and installation costs for PV battery systems were considered with a 15% increased fixed capital cost and the actual costs of the batteries. The fixed capital cost was, in our case, defined as the turnkey cost excluding the costs for the main components (PV modules, inverter and batteries), standing for about 47.5% of the turnkey cost. The costs of the batteries were modeled with a linear cost function where a 5 kWh battery cost 6.7 SEK/Wh and a 20 kWh battery cost 4.2 SEK/Wh.

For multi-year simulations, the PV and PV battery systems were modeled with inverter and battery prices based on data from our own market survey, where we used the lowest available retail prices. PV module costs were modeled based on retail prices provided in the National PVPS report for Sweden from 2019 [1]. The fixed capital costs for PV battery systems were modeled as in the pre-sizing, with an extra charge of 15% for higher installation and transport costs.

2.5. Incentives and Subsidies

In Sweden, investments in small-scale, residential, grid-connected PV and PV battery systems are supported by income tax credits. Currently, a tax credit of 15% on the material and installation costs including VAT is granted for small, grid-connected PV systems without batteries. As a rule of thumb, the tax office considers 3% of the turnkey system cost as not for materials or the installation, so typically, a 14.55% income tax reduction on the turnkey cost is granted. Residential battery systems enjoy a tax reduction of 50%, which can even include the cost of the hybrid inverter and its installation. Here, 3% of the turnkey cost is deducted by the tax office, considered as representing costs that are not for materials or installation, so typically, a 48.5% income tax reduction can be obtained for battery and hybrid inverters. The total income tax reduction is limited to 50,000 SEK per person each year.

In our simulations, the 14.55% income tax reduction on the turnkey cost of grid-connected PV systems without batteries was applied. For grid-connected PV battery systems, a 14.55% tax reduction for the PV modules, and 80% of the fixed capital cost excluding the batteries and hybrid inverter, was applied. The 48.5% tax reduction was used for the battery and inverter cost and 20% of the fixed capital cost. Normally, a tax reduction of 50,000 SEK/year can be obtained. Yet, we assumed in the cost modeling that a tax reduction of 100,000 SEK could be obtained since it is possible to distribute the installation over two years. Table 2 shows the tax reductions that were used for the different loads and system sizes.

Table 2. Subsidies used in the cost modeling.

	Load 1				**Loads 2 and 4**				**Load 3**			
Battery size (kWh)	0	5	10	15	0	5	10	15	0	5	10	15
Subsidy used (SEK)	33,716	58,065	65,291	71,596	23,341	68,082	75,308	81,613	41,496	81,255	88,481	94,786

2.6. Financial Parameters

Pre-sizing and multi-year simulations were performed for a project life of 30 years, inflation rate of 2% and discount rate of 3.5%. In addition, the multi-year simulations were conducted with an annual electricity price increase of 3.5%, based on the price development between 2000 and 2018. Component replacement costs were assumed to be 15% lower for the inverter and 30% lower for the batteries.

3. Modeling and Simulation

An overview of the modeling and simulation approach is given in Figure 2. In the pre-sizing part, the purpose was to find the optimal sizing of grid-connected PV systems with and without batteries for the given boundary conditions. This was done with the auto-sizing function in HOMER Grid, which finds the system size with the lowest net present cost (NPC). In contrast to the multi-year simulations, the pre-sizing simulations were done for one year and the results were then extrapolated for the whole project life. Pre-sizing was carried out to reduce the number of variables for the multi-year simulation system. Using the multi-year simulation feature in HOMER Grid systems, the PV and PV battery systems were modeled in more detail and considering time, depending on phenomena such as PV module and battery degradation, price fluctuations of the grid and electricity and fuel costs.

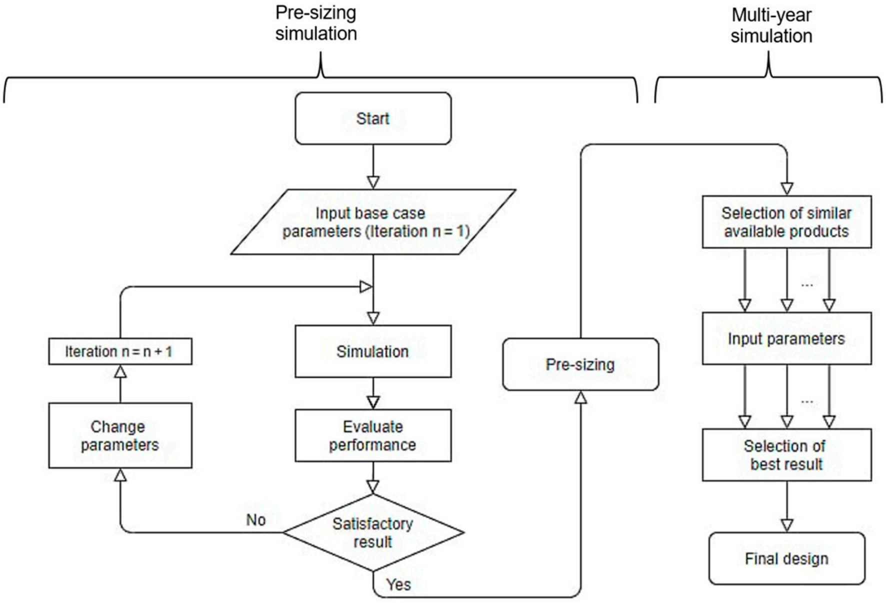

Figure 2. Sizing and optimization procedure.

3.1. Pre-Sizing Results

Pre-sizing was carried out for the PV and PV battery systems for all four load profiles and all three tariff structures, as shown in Tables 3 and 4. Not unexpectedly, the optimal PV size, for both PV and PV battery systems, corresponded to PV sizes that approximately, for one year, would generate as much electricity as was consumed. This was because the 0.6 SEK/kWh tax credit for exported electricity applies as long as production does not exceed consumption. If production exceeds consumption, the production surplus is not granted the tax credit and compensation is then only based on the spot price. HOMER Grid maximizes the PV sizes independently, whether there is a battery or not, as revenues for exported electricity are almost the same as savings on self-consumed electricity. The optimal size of the batteries in the PV battery system varies depending on the tariff structure and the load profile. High demand charges, as modeled for utility 1, for two of the load profiles, promoted a slightly larger battery size, whereas, for the other load profiles, the battery size was the same for the higher and lower demand-charge tariffs.

Table 3. Results of pre-sizing grid-connected PV systems without batteries (GRID-PV-ONLY).

	Load 1			**Load 2**			**Load 3**			**Load 4**		
Tariff (Utility)	1	2	3	1	2	3	1	2	3	1	2	3
Total load (kWh)	11,220			7479			13,487			7493		
PV size (kW)	13	13	13	9	9	9	16	16	16	9	9	9
Initial capital (SEK)	151,946			108,635			183,952			108,005		
NPC (SEK)	374,863	340,135	324,291	340,602	283,087	252,385	423,618	377,986	375,229	292,397	268,695	253,538

Table 4. Results of pre-sizing grid-connected PV battery systems (GRID-PV-BAT).

	Load 1			**Load 2**			**Load 3**			**Load 4**		
Tariff (Utility)	1	2	3	1	2	3	1	2	3	1	2	3
Total load (kWh)	11,220			7479			13,487			7493		
PV size (kW)	13	13	13	9	9	9	16	16	16	9	9	9
Battery size (kWh)	10	6	1	8	6	1	8	8	1	6	6	1
Initial capital (SEK)	177,383	169,932	161,569	128,532	124,689	116,150	207,254	207,518	194,955	124,637	123,776	116,150
NPC (SEK)	361,408	353,327	344,937	302,901	283,155	270,924	419,007	396,843	397,180	288,416	276,066	272,654

3.2. Modeling and Simulation Approach for Optimized Systems

In the second step of the system modeling and simulation, the pre-sized systems were further optimized and modeled in greater detail. Instead of using generic components for the battery and inverter charger, concrete products were now used. Originally, data for four lithium battery brands and three hybrid inverters were identified, but in the end, products from only one supplier were chosen, giving the lowest turnkey costs.

Most other input values for the system modeling were described in Sections 2 and 3.1.

This study aimed to evaluate the techno-economic feasibility of grid-connected, distributed PV battery systems. To compare those with alternative solutions, three general system architectures were modeled, simulated and compared:

- ONLY-GRID: The building has no PV system and no batteries. All electricity is provided by the utility;
- GRID-PV-ONLY: The grid-connected PV systems are without batteries, with the PV arrays sized according to the pre-sizing results for the four loads;
- GRID-PV-BAT: Grid-connected PV battery systems are used, which are preliminarily sized according to the pre-sizing results and then further optimized for various sensitivity parameters.

Simulations were performed with the inputs and boundary conditions described above. In addition, two variants were simulated to include possible future scenarios. Two scenarios were kept in mind. First, we expected that demand charges will become more popular and that these charges will increase. Second, we speculated that the 0.6 SEK tax credit for excess electricity will soon be reduced or removed. Therefore, more simulations with a doubled demand charge tariff and canceled tax credit for excess electricity were performed.

3.3. Battery Control

HOMER Grid uses a combination of strategies to optimize the use of batteries. It looks 48 h into the future and adapts the charging and discharging depending on the load demand, available PV and costs for the grid electricity, to cover the load with as little cost as possible. It also looks ahead for surplus electricity from the PV modules and tries to leave space in the batteries to capture this surplus. When demand charges exist, HOMER Grid will reduce peak loads by calculating and applying a demand power limit each month. This demand power limit is based on the available PV and battery capacity at the time the peaks occur so that the full demand can always be served. The overall control target is to reduce the net present cost and achieve the lowest levelized cost of energy.

Figures 3 and 4 illustrate the battery dispatch strategy on two example days in spring and early summer. For every month, HOMER Grid defines a grid demand limit and uses the batteries to restrict the electricity purchase to that limit. Both PV and grid electricity are used for balancing.

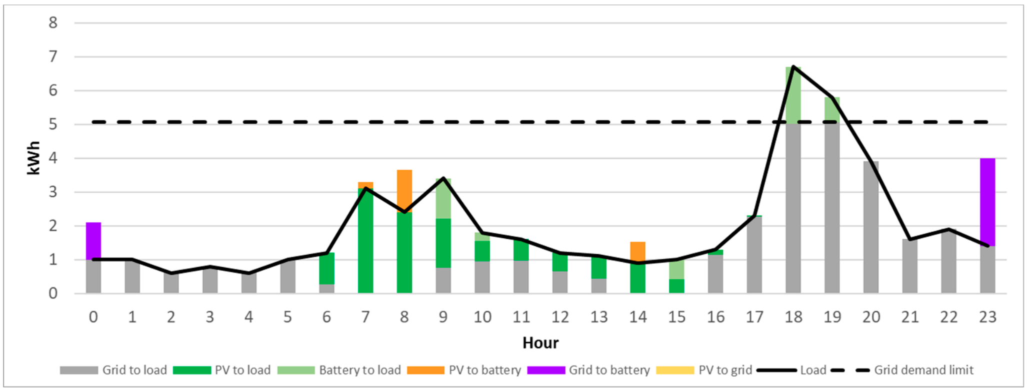

Figure 3. Hourly energy flow for 29 March, load profile 1, utility 1.

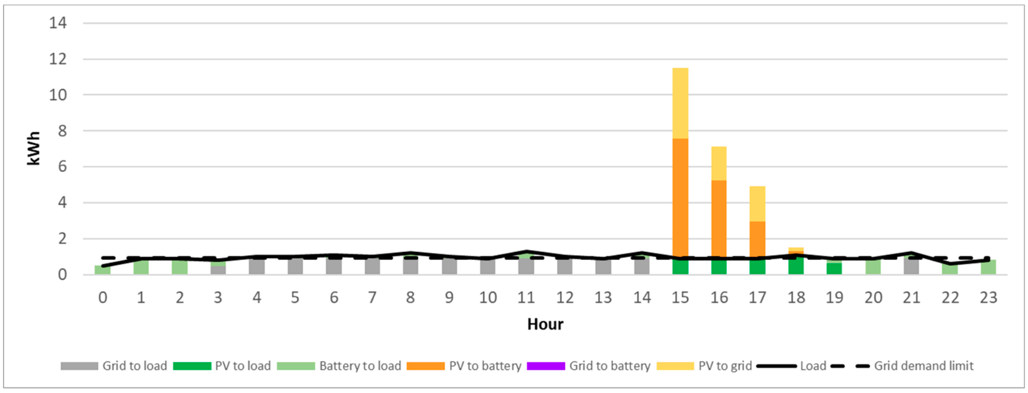

Figure 4. Hourly energy flow for 1 June, load profile 1, utility 1.

3.4. Economic Evaluation Method, Net Present Cost and Cash

The cumulative discounted cash flow was used to analyze the economic performance of the various system solutions. The discounted cash flow included the present value of all the costs the system incurs over its lifetime, minus the present value of all the revenue it earns over its lifetime. The method thus allowed us to visualize the evolution of the system owner's earnings and expenses during the project's lifetime, adjusted for the time-value of money. The sum of the annual cumulative cash flow values during the project life is the net present cost (NPC), which is used by HOMER Grid to optimize, compare and rank energy systems. The NPC is a simplified LCC method that does not include parameters such as disposal and recycling costs or social and environmental costs, even though emission penalties could be included by HOMER Grid.

The simulations results for the various system variants were evaluated and compared with the help of the annual net savings. The annual net savings are the difference in net present costs of the studied system compared to the net present costs of the reference case (ONLY-GRID), divided by the years of the project's life. In the sensitivity part of this study, GRID-PV-ONLY was also used as a reference, particularly to evaluate the sizing of the battery.

4. Results

4.1. Impact of Load Profile and Demand Tariff

In the first stage of the multi-year simulations, grid-connected PV battery systems were simulated for the four load profiles and one tariff structure without demand tariffs. In addition, the size of the battery was varied with 5, 10 and 15 kWh. For each case, the PV without batteries (GRID-PV-ONLY) and the reference case with pure grid supply (ONLY-GRID) were also simulated. Figure 5 shows the cumulative discounted cash flow for the demand tariff of utility 1 and the four load profiles. Figure 6, meanwhile, shows the cumulative discounted cash flow for the demand charge tariff of utility 2 and the four load profiles. The purple curves illustrate the discounted cash flow for the reference case. The values at year 30 indicate the total discounted cost (NPC) for each system variant. Changes in the linearity of the cash flow are due to inverter and battery replacements. Inverters are replaced after 15 years and batteries after 8–14 years, depending on the energy throughput. It can clearly be seen that both PV and PV battery systems have a much lower NPC than the reference system. The actual payback time is given by the crossing points of the curves for each PV system with the curve of the reference system. For utility 1, the payback times varied between 12 and 17 years depending on the system architecture and load profile. For utility 2, the payback times varied between 13 and 19 years depending on the system architecture and the load profile, indicating that the lower demand charges of utility 2 gave slightly lower profitability for the PV battery systems. The load characteristics had a significant impact on the results. All load profiles had higher peak loads in the winter than in the summer, but load 2 had also high peak loads during the rest of the year when compared to the other load profiles. Analysis of the tariffs of utility 1 showed that while the NPCs for loads 1, 3 and 4 were very similar for both the GRID-PV-Only and Grid-PV-BAT systems, they were somewhat lower for the 10 kWh and 15 kWh Grid-PV-BAT systems with load 2.

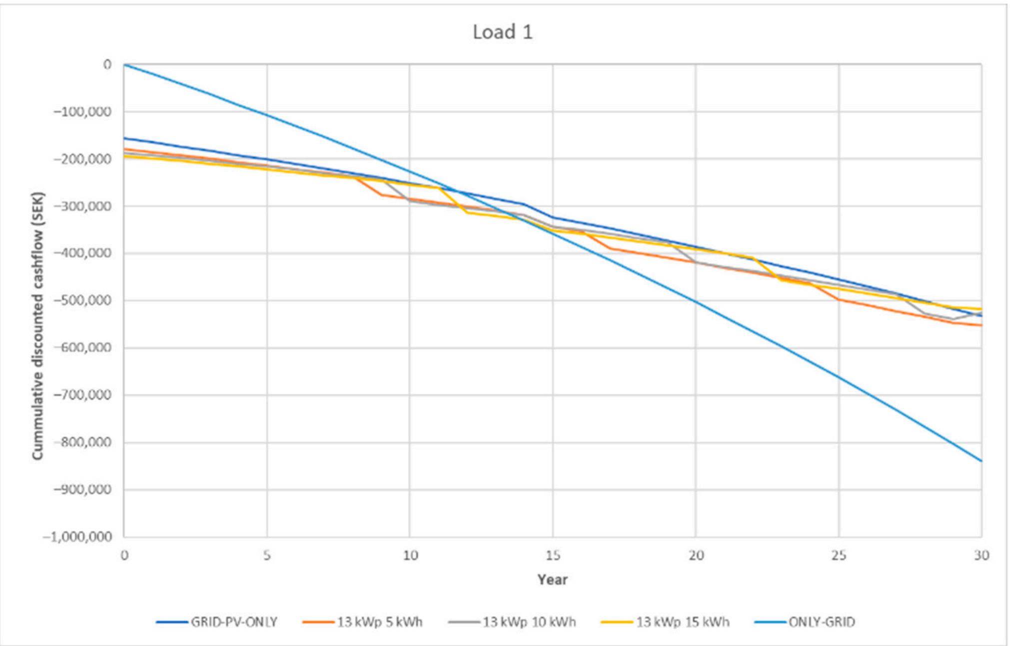

Figure 5. *Cont.*

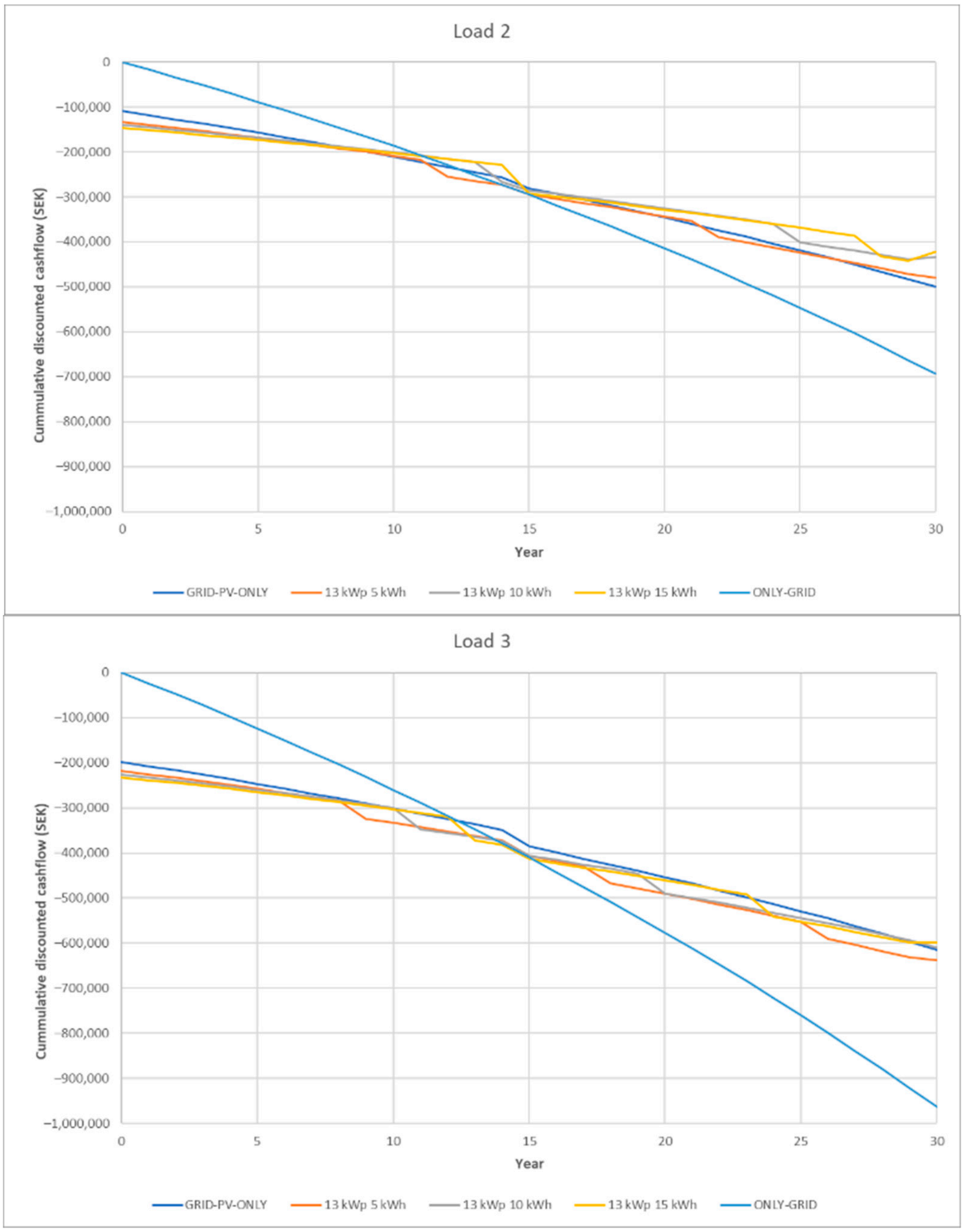

Figure 5. *Cont.*

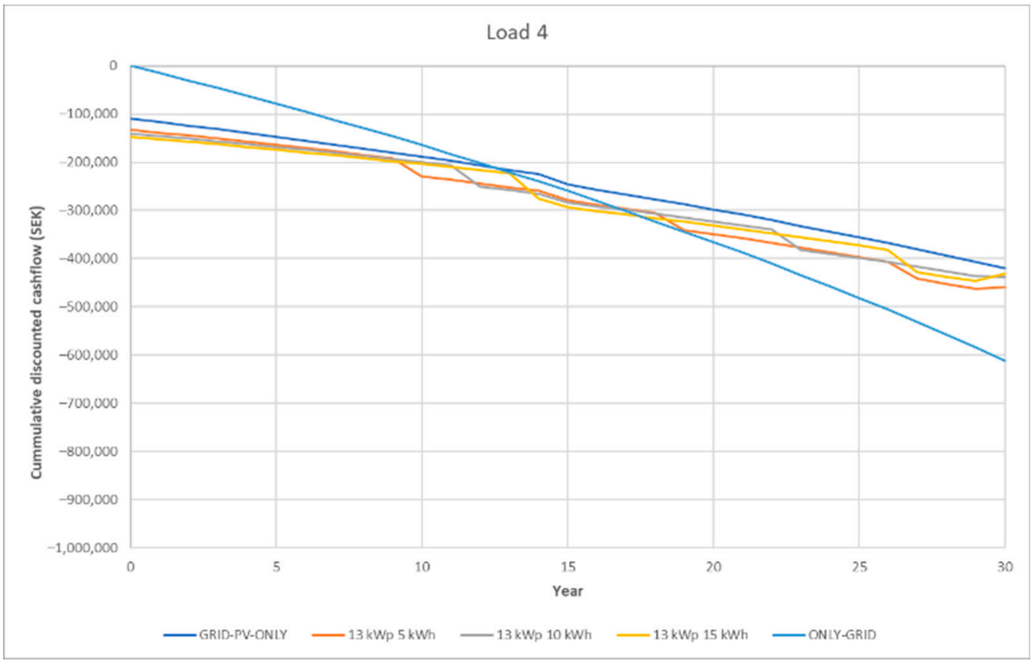

Figure 5. Cumulative cash flow for four load profiles with tariffs of utility 1.

Utility 2 had lower demand charges that made GRID-PV-BAT systems for all load profiles less profitable than a GRID-PV-ONLY system, even for load 2. However, the difference in NPC was barely significant for the 10 and 15 kWh GRID-PV-BAT system when compared to the GRID-PV-ONLY system. At year 30, the NPC of the GRID-PV-BAT systems could slightly increase depending on when the batteries were replaced and how much salvage value remained for them by the end of the project's life.

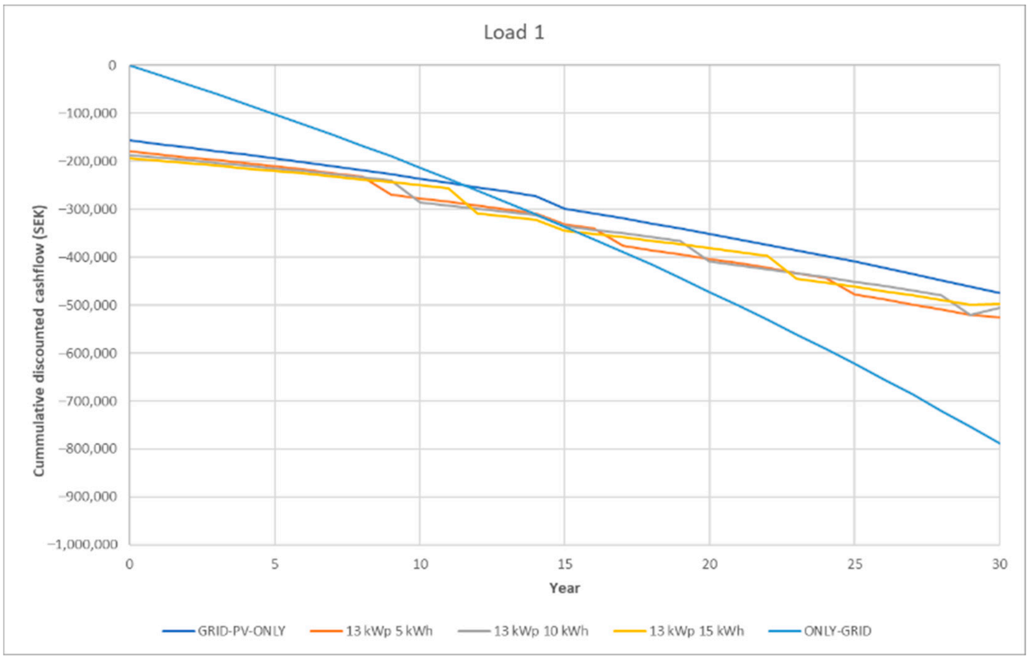

Figure 6. *Cont.*

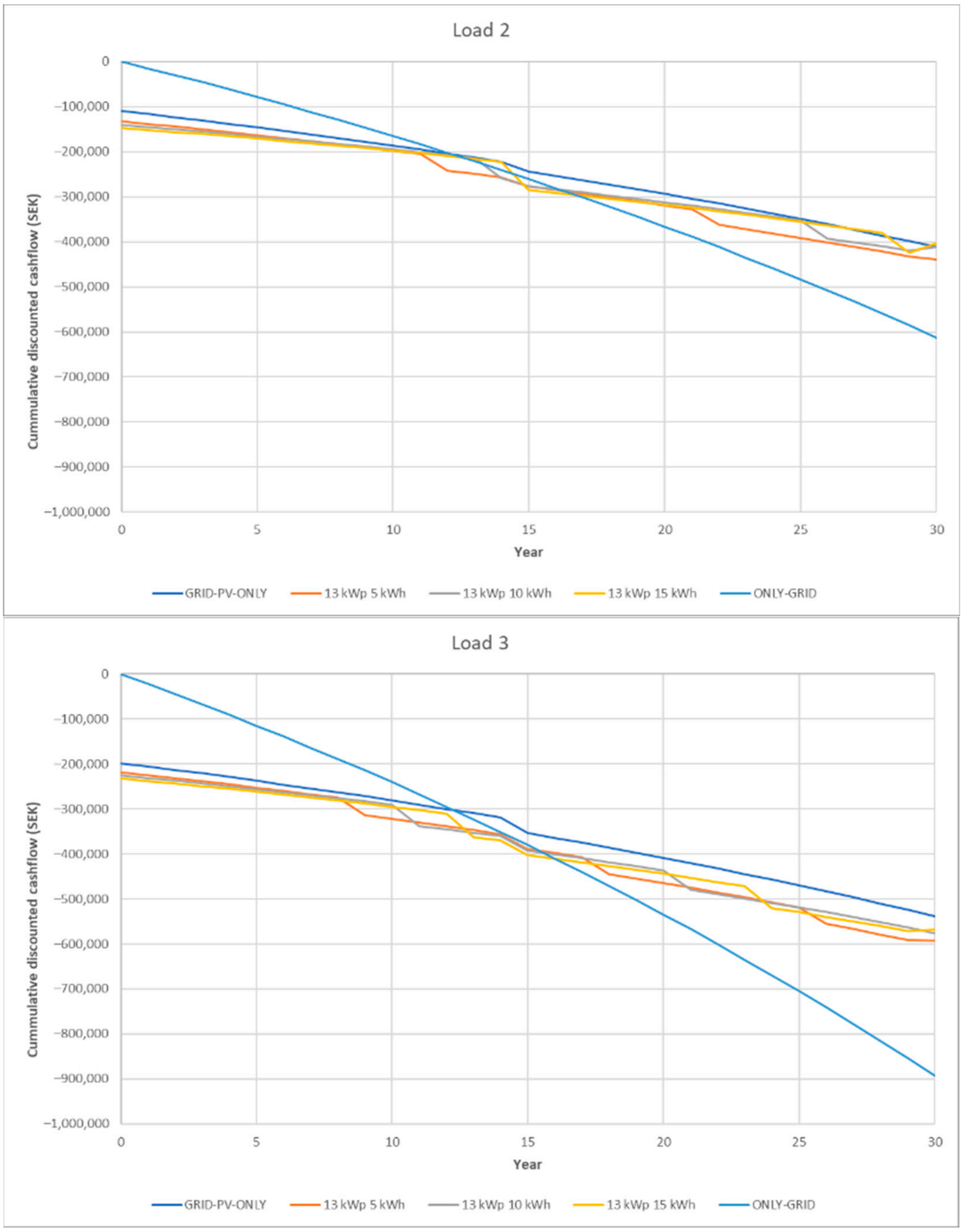

Figure 6. *Cont*.

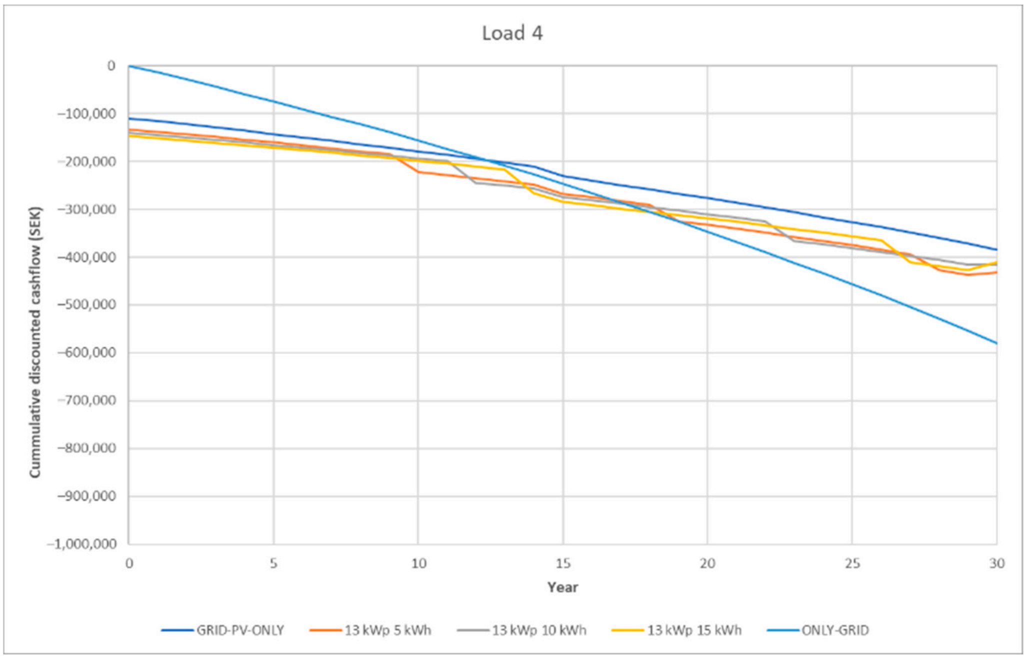

Figure 6. Cumulative cash flow for four load profiles with tariffs of utility 2.

Figure 7 shows even more clearly the impact of the load profile on the profitability by displaying the total savings compared to the reference system. In the figures, we include the results for the third utility without demand charges. It becomes obvious that GRID-PV-BAT systems only had a significant advantage compared to GRID-PV-ONLY systems if there were sufficient peaks for all seasons of the year. Load profiles 1 and 3 gave very similar savings. The highest savings were achieved without a battery if no demand charges were applied or if the demand charges were relatively low. With higher demand charges, as for utility 1, the system solution with the highest battery capacity gave the greatest savings. This was also true for load profile 2 but the impact of the tariff structure was more significant.

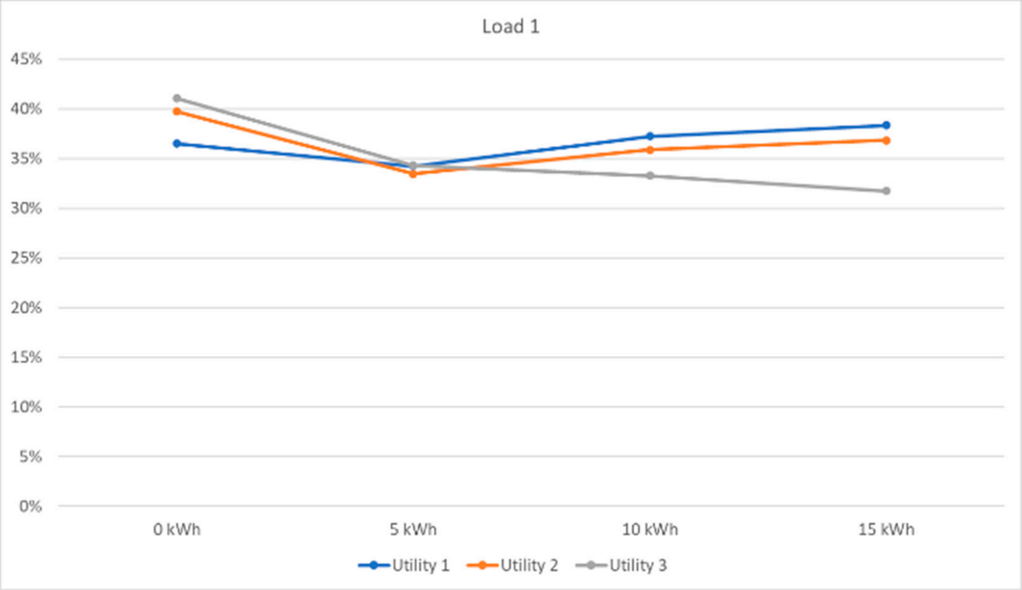

Figure 7. *Cont*.

Figure 7. Total savings for the four load profiles and the tariffs of all three utilities.

In Figure 8, the annual costs for load 1 and utility 1 are shown, highlighting the cost distribution for each solution. It can clearly be seen how energy charges were reduced by the GRID-PV-ONLY system, and that the demand charges were reduced by adding batteries. The total annual costs including investment and replacement costs were very similar for all PV and PV battery systems and significantly lower than for the reference system. The cost of energy charges shown in Figure 8 represents the cost of purchasing electricity minus the income from exported electricity. There was barely any difference between the energy costs with or without batteries. This was due to the tax credit of 0.6 SEK/kWh, which equalized the value of 1 kWh of self-consumed electricity with 1 kWh of exported electricity.

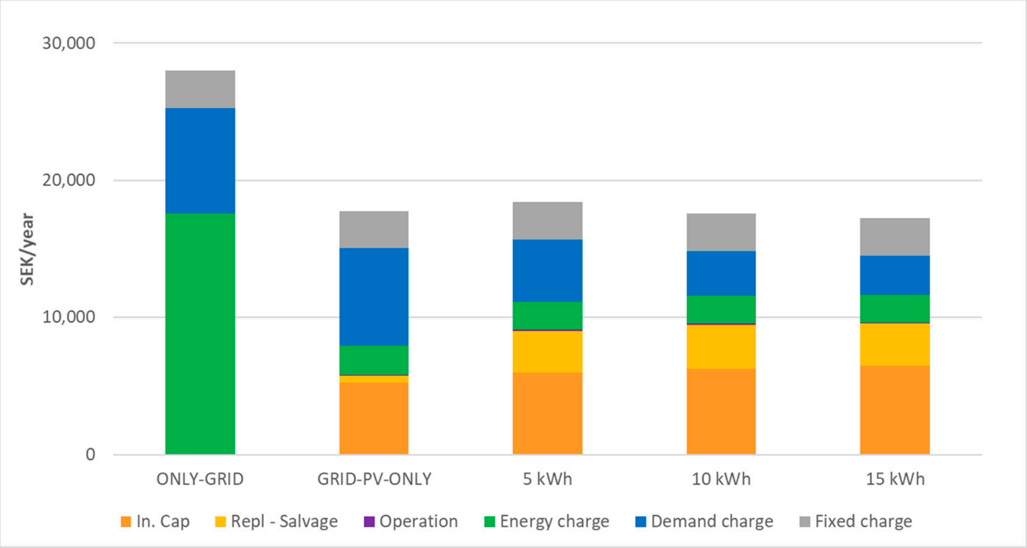

Figure 8. Discounted annual cost details for load 1, utility 1.

4.2. Tax Credit and Demand Charge Increase

The tax credit of 0.6 SEK/kWh for exported electricity is a rather substantial part of the compensation for owners of small residential PV systems in Sweden—that could be removed by the authorities at any time. As expected, simulations without this tax credit revealed that the profitability of all PV systems would be drastically reduced. Figure 9 compares load 1 and the GRID-PV-BAT system with 5 kWh for the three utilities with and without the tax credit.

With the originally defined boundary conditions, net savings of 32–42% compared to the reference systems could be achieved, depending on the utility and system size. Figures 10 and 11 shows these savings when compared to those with the 0.6 SEK tax credit removed. The savings in the new scenario reduced significantly, but savings of 10–22% could still be achieved compared to ONLY GRID. The highest savings were achieved for cases with high demand charges and large battery sizes, with reduced demand charges and amounts fed to the grid. Increased self-consumption alone, as in the case of utility 3, did not compensate for the extra costs of the battery storage. Figures 12 and 13 shows even more clearly the boundary conditions and battery sizes for which the use of batteries made sense, showing the savings when compared with GRID-PV-ONLY systems. Without demand charges, batteries gave no extra savings; with a demand charge, it depended on the size of the battery and whether or not there was a tax credit for the electricity fed to the grid. The largest savings were achieved with a 15 kWh battery, high demand charges and no tax credits.

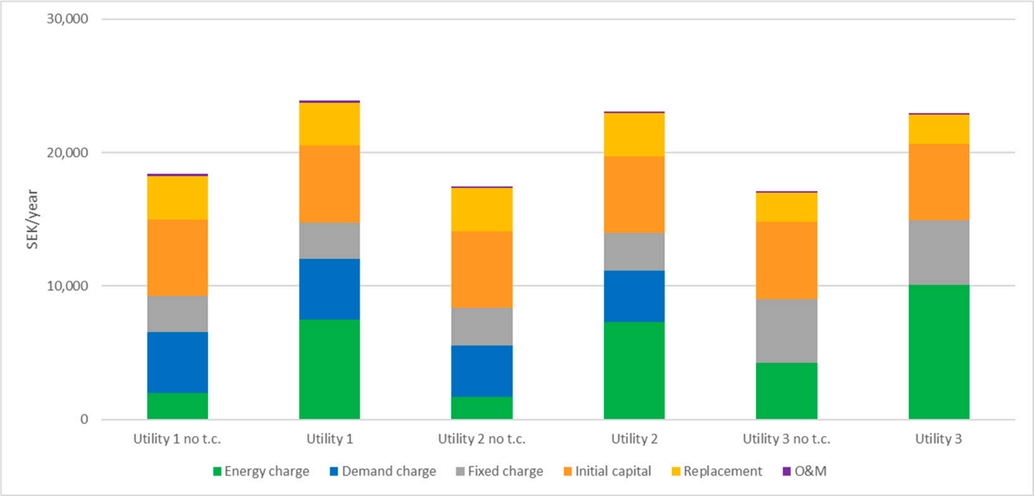

Figure 9. Impact of tax credit on annual costs.

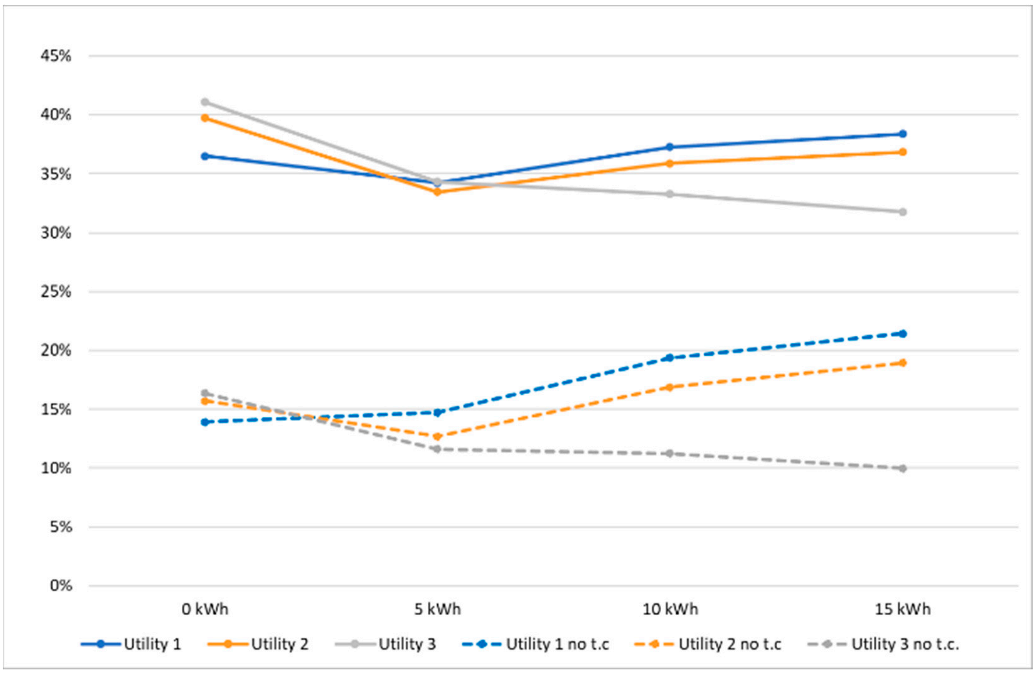

Figure 10. Annual net savings with and without tax credit for load 1, compared to ONLY-GRID.

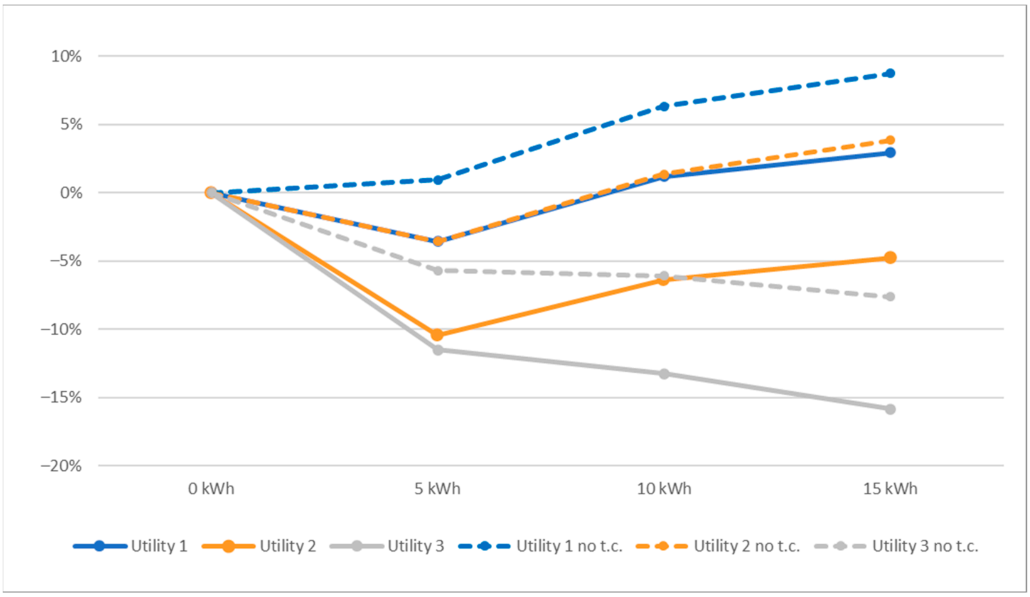

Figure 11. Annual net savings with and without tax credit for load 1, compared to GRID-PV-Only.

The profitability of GRID-PV-BAT systems was also studied for higher demand charges by doubling the demand fees for utilities 1 and 2. Figure 12 shows the savings compared to the reference system (ONLY-GRID). The savings decreased for the GRID-PV-ONLY system, while the savings for the GRID-PV-BAT systems increased. Figure 13 shows the impact of the battery size on the changes in savings compared to GRID-PV-ONLY. With the doubled demand charges, all GRID-PV-BAT systems had equal or greater savings than the GRID-PV-ONLY solution. GRID-PV-BAT solutions with 10 kWh or 15 kWh had significantly higher savings than the GRID-PV-ONLY system.

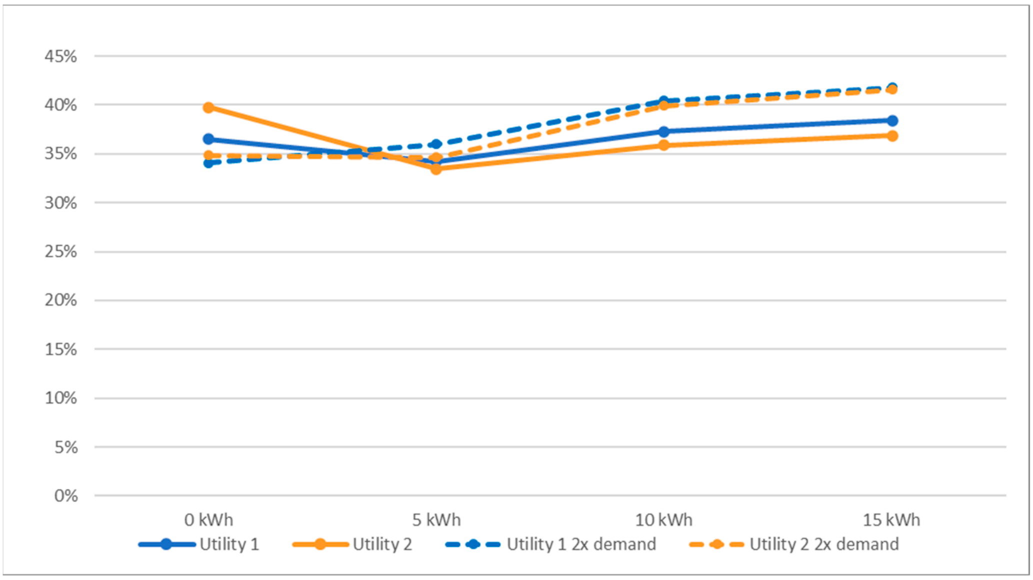

Figure 12. Annual net savings with and without doubled demand charges, compared to GRID-ONLY.

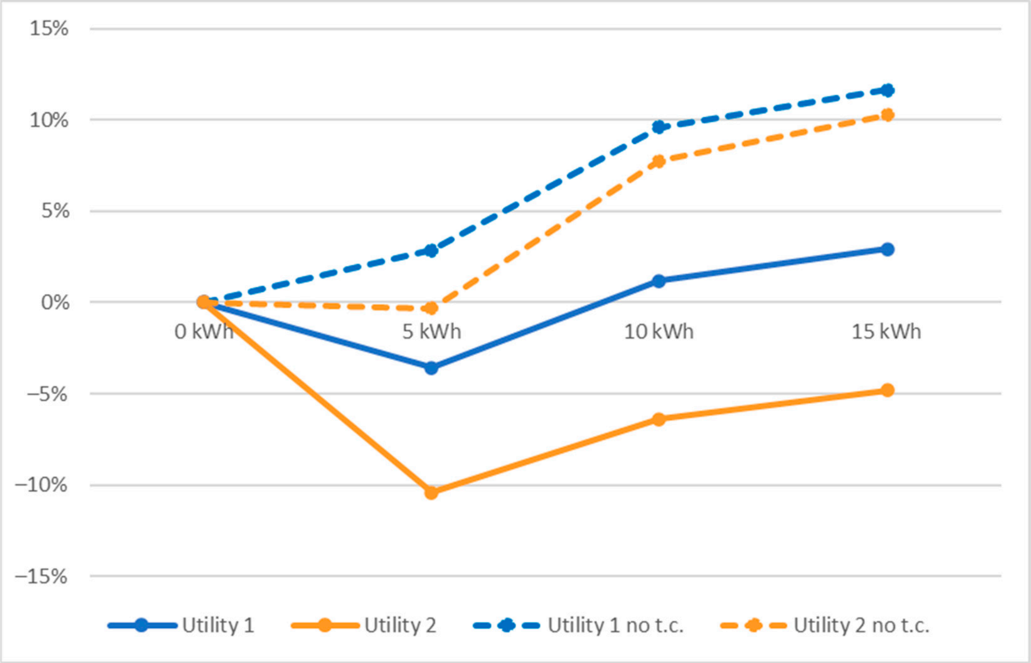

Figure 13. Annual net savings with and without doubled demand charges, compared to GRID-PV-ONLY.

5. Discussion and Conclusions

The purpose of this research was to investigate if grid-connected residential PV battery systems could be profitable for leisure homes in Swedish mountainous areas where utilities have started to apply demand charges to meet the increasing peak demands. The results show that battery systems are highly profitable in such environments and that the profitability depends on the level of demand charges, available tax credits and load profile. Load profiles with peaks throughout the whole year give higher profitability than only peaks during the winter season. PV batteries systems are also profitable for cases where no demand charges are applied, but the savings are significantly lower compared to GRID-PV-ONLY systems. As there are savings, in contrast to findings from previous studies [10,12], it becomes clear that decreasing investment costs, together with favorable subsidies, have turned the page for residential PV batteries in Sweden. As demand charges are increasingly introduced by the utilities in Sweden, it can be expected that PV battery systems will also become profitable for single-family homes, especially when there are regular peak loads, such as for homes charging an electric vehicle. Moreover, electricity prices and price variations increased drastically in the second half of 2021. Even if price levels return to a lower level, it can be expected that the increase in the electricity demand, to meet the electricity needs of the transport sector and for the decarbonization of the steel and construction industries, along with the increasing demands of other sectors, will lead to electricity prices that are higher than the assumed annual increase of 3.5% per year that was used in the simulations.

Yet, the good profitability we showed still greatly depends on the government support for these systems through a tax credit for surplus electricity and investment costs. However, lower compensation for electricity exported to the grid benefits PV battery systems as it allows for higher self-usage of PV electricity. Doubling the demand tariffs will further encourage the use of batteries by reducing the NPC and significantly increasing the savings compared to PV systems without batteries, especially for larger battery sizes.

The results that were obtained in this study were based on the advanced battery dispatch control strategy used by HOMER Grid, which includes forecasting peak loads and electricity prices. Such advanced control is not yet fully implemented in currently available products but should be possible to implement with common machine-learning algorithms.

In this study, batteries were only used for peak shaving and increased PV self-consumption. The profitability of grid-connected PV battery systems could certainly further increase when offering additional services for the utilities, such as frequency control support and peak hour demand reduction. Especially in holiday locations, the recent construction boom has led to grid capacity problems during peak demand hours.

Grid-connected PV battery systems in Sweden are today highly subsided by tax credits and are becoming increasingly popular in the field of PV installations. A likely and even more cost-effective alternative to stationary battery storage will be electrical vehicles with V2G (vehicle-to-grid) capability. Peak demand occurs mostly due to occupancy behavior, and when people are at home, the car battery should be available for peak shaving.

Author Contributions: Conceptualization, F.F. and J.C.M.; Methodology, F.F. and J.C.M.; Simulations, J.C.M. Analysis, F.F. and J.C.M.; Writing—original draft preparation, F.F.; Writing—review and editing, F.F. and J.C.M.; Visualization, J.C.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Dalarna University, the Swedish Agency for Economic and Regional Growth and the Region of Dalarna.

Data Availability Statement: No data reported.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lindahl, J.; Dahlberg Rosell, M.; Oller Westerberg, A. National Survey Report of PV Power Applications in Sweden 2019. 2020. Available online: www.iea-pvps.org (accessed on 12 October 2021).
2. Berard, J. 22,000 Nya Nätanslutna Solcellsanläggningar. Statistic Update for PV Installations in Sweden. 2021. Available online: https://www.energimyndigheten.se/nyhetsarkiv/2021/22-000-nya-natanslutna-solcellsanlaggningar-under-2020/ (accessed on 7 May 2021).
3. BSW. Solar Battery Boom. Bundesverband Solarwirtschaft. Available online: https://www.solarwirtschaft.de/en/2021/02/18/solar-battery-boom/ (accessed on 7 May 2021).
4. d'Halluin, P.; Rossi, R.; Schmela, M. European Market Outlook for Residential Battery Storage 2020–2014. 2020. Available online: moz-extension://6b7c6d3c-3b38-4b91-a195-a2f9b4ffe12b/enhanced-reader.html?openApp&pdf=https%3A%2F%2Fapi.solarpowereurope.org%2Fuploads%2F2820_SPE_EU_Residential_Market_Outlook_07_mr_4397be13cf.pdf (accessed on 28 March 2022).
5. Zhang, Y.; Lundblad, A.; Campana, P.E.; Benavente, F.; Yan, J. Battery sizing and rule-based operation of grid-connected photovoltaic-battery system: A case study in Sweden. *Energy Convers. Manag.* **2017**, *133*, 249–263. [CrossRef]
6. Nyholm, E.; Goop, J.; Odenberger, M.; Johnsson, F. Solar photovoltaic-battery systems in Swedish households—Self-consumption and self-sufficiency. *Appl. Energy* **2016**, *183*, 148–159. [CrossRef]
7. Widén, J.; Wäckelgård, E.; Lund, P.D. Options for improving the load matching capability of distributed photovoltaics: Methodology and application to high-latitude data. *Sol. Energy* **2009**, *83*, 1953–1966. [CrossRef]
8. Thygesen, R.; Karlsson, B. Simulation and analysis of a solar assisted heat pump system with two different storage types for high levels of PV electricity self-consumption. *Sol. Energy* **2014**, *103*, 19–27. [CrossRef]
9. Psimopoulos, E.; Bee, E.; Widén, J.; Bales, C. Techno-economic analysis of control algorithms for an exhaust air heat pump system for detached houses coupled to a photovoltaic system. *Appl. Energy* **2019**, *249*, 355–367. [CrossRef]
10. Heinisch, V.; Odenberger, M.; Göransson, L.; Johnsson, F. Prosumers in the electricity system-household vs. system optimization of the operation of residential photovoltaic battery systems. *Front. Energy Res.* **2019**, *6*, 145. [CrossRef]
11. Fascì, M.L. Feasibility Study of Battery Storage Installed with Solar PV in an Energy Efficient House. 2017. Available online: http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-209922 (accessed on 11 May 2021).
12. Luthander, R.; Lingfors, D.; Munkhammar, J.; Widén, J. Self-Consumption Enhancement of Residential Photovoltaics with Battery Storage and Electric Vehicles in Communities. In Proceedings of the Eceee 2015 Summer Study on Energy Efficiency, Toulon/Hyères, France, 1–6 June 2015; pp. 991–1002. Available online: https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2015/5-energy-use-in-buildings-projects-technologies-and-innovation/self-consumption-enhancement-of-residential-photovoltaics-with-battery-storage-and-electric-vehicles-in-communiti (accessed on 11 May 2021).
13. Lovati, M.; Zhang, X. Impact of electrical vehicle (EV) penetration on the cost-optimal building integrated photovoltaics (BIPV) at a small residential district in Sweden. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *609*, 072066. [CrossRef]
14. Luthander, R.; Forsberg, S. The Potential of Using Residential PV-Battery Systems to Provide Primary Frequency Control on a National Level. 2018. Available online: http://solarintegrationworkshop.org/ (accessed on 18 September 2021).

15. Jaris, K.; Abdallah, A. Analys, Utredning och Effektivisering av Nättariffer i Vallentuna. 2016. Available online: http://www.diva-portal.org/smash/get/diva2:947216/FULLTEXT01.pdf (accessed on 17 May 2021).
16. Luthander, R.; Widén, J.; Munkhammar, J.; Lingfors, D. Self-consumption enhancement and peak shaving of residential photovoltaics using storage and curtailment. *Energy* **2016**, *112*, 221–231. [CrossRef]
17. Koskela, J.; Lummi, K.; Mutanen, A.J.; Rautiainen, A.; Jarventausta, P. Utilization of Electrical Energy Storage With Power-Based Distribution Tariffs in Households. *IEEE Trans. Power Syst.* **2019**, *34*, 1693–1702. [CrossRef]
18. Hledik, R.; Greenstein, G. The distributional impacts of residential demand charges. *Electr. J.* **2016**, *29*, 33–41. [CrossRef]
19. Bertsch, V.; Geldermann, J.; Lühn, T. What drives the profitability of household PV investments, self-consumption and self-sufficiency? *Appl. Energy* **2017**, *204*, 1–15. [CrossRef]
20. Weniger, J.; Tjaden, T.; Bergner, J.; Quaschning, V. Sizing of Battery Converters for Residential PV Storage Systems. *Energy Procedia* **2016**, *99*, 3–10. [CrossRef]
21. Truong, C.N.; Naumann, M.; Karl, R.C.; Müller, M.; Jossen, A.; Hesse, H.C. Economics of Residential Photovoltaic Battery Systems in Germany: The Case of Tesla´s Powerwall. *Batteries* **2016**, *2*, 14. [CrossRef]
22. Schopfer, S.; Tiefenbeck, V.; Staake, T. Economic assessment of photovoltaic battery systems based on household load profiles. *Appl. Energy* **2018**, *223*, 229–248. [CrossRef]
23. Moshövel, J.; Kairies, K.-P.; Magnor, D.; Leuthold, M.; Bost, M.; Gährs, S.; Szczechowicz, E.; Cramer, M.; Sauer, D.U. Analysis of the maximal possible grid relief from PV-peak-power impacts by using storage systems for increased self-consumption. *Appl. Energy* **2015**, *137*, 567–575. [CrossRef]
24. Li, J.; Danzer, M.A. Optimal charge control strategies for stationary photovoltaic battery systems. *J. Power Sources* **2014**, *258*, 365–373. [CrossRef]
25. Kaschub, T.; Jochem, P.; Fichtner, W. Solar energy storage in German households: Profitability, load changes and flexibility. *Energy Policy* **2016**, *98*, 520–532. [CrossRef]
26. Dietrich, A.; Weber, C. What drives profitability of grid-connected residential PV storage systems? A closer look with focus on Germany. *Energy Econ.* **2018**, *74*, 399–416. [CrossRef]
27. O'Shaughnessy, E.; Cutler, D.; Ardani, K.; Margolis, R. Solar plus: A review of the end-user economics of solar PV integration with storage and load control in residential buildings. *Appl. Energy* **2018**, *228*, 2165–2175. [CrossRef]
28. Foles, A.; Fialho, L.; Collares-Pereira, M. Techno-economic evaluation of the Portuguese PV and energy storage residential applications. *Sustain. Energy Technol. Assessments* **2020**, *39*, 100686. [CrossRef]
29. Tervo, E.; Agbim, K.; DeAngelis, F.; Hernandez, J.; Kim, H.K.; Odukomaiya, A. An economic analysis of residential photovoltaic systems with lithium ion battery storage in the United States. *Renew. Sustain. Energy Rev.* **2018**, *94*, 1057–1066. [CrossRef]
30. Chaianong, A.; Bangviwat, A.; Menke, C.; Breitschopf, B.; Eichhammer, W. Customer economics of residential PV—Battery systems in Thailand. *Renew. Energy* **2020**, *146*, 297–308. [CrossRef]
31. Puranen, P.; Kosonen, A.; Ahola, J. Techno-economic viability of energy storage concepts combined with a residential solar photovoltaic system: A case study from Finland. *Appl. Energy* **2021**, *298*, 117199. [CrossRef]
32. Kuleshov, D.; Peltoniemi, P.; Kosonen, A.; Nuutinen, P.; Huoman, K.; Lana, A.; Paakkonen, M.; Malinen, E. Assessment of economic benefits of battery energy storage application for the PV-equipped households in Finland. *J. Eng.* **2019**, *2019*, 4927–4931. [CrossRef]
33. Ren, Z.; Grozev, G.; Higgins, A. Modelling impact of PV battery systems on energy consumption and bill savings of Australian houses under alternative tariff structures. *Renew. Energy* **2016**, *89*, 317–330. [CrossRef]
34. Li, Y.; Gao, W.; Ruan, Y. Performance investigation of grid-connected residential PV-battery system focusing on enhancing self-consumption and peak shaving in Kyushu, Japan. *Renew. Energy* **2018**, *127*, 514–523. [CrossRef]
35. HOMER Grid | Design and Optimization Software for Solar, Energy Storage and Microgrids. Available online: https://www.homerenergy.com/products/grid/index.html (accessed on 18 May 2021).
36. JRC Photovoltaic Geographical Information System (PVGIS)—European Commission. Available online: https://re.jrc.ec.europa.eu/pvg_tools/en/ (accessed on 12 June 2021).
37. Normal globalstrålning under ett år | SMHI. Available online: https://www.smhi.se/data/meteorologi/stralning/normal-globalstralning-under-ett-ar-1.2927 (accessed on 27 February 2021).
38. Lindahl, J.; Stoltz, C. *National Survey Report of PV Power Applications in Sweden 2017*; Swedish Energy Agency: Eskilstina, Sweden, 2017.