The potential for balancing the Swedish power grid with residential home batteries

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Abstract

This paper presents the potential for prosumer batteries coupled to PV units to cover the national frequency balancing needs in Sweden. PV coupled residential batteries are found to be profitable with today's prices, if granted access to balancing markets. Simulations are based on national targets for solar PV production in 2040 (5-10 TWh, 5-10% of electric consumption) and current residential PV share of total installed PV capacity. In the study battery attachment rate was 50% and 15% of single family houses were equipped with 10 kW PV installation with a battery capacity of 6 kW / 7.68 kWh. In total, the battery PV systems constituted 25% of total installed capacity of PV in 2040. The results showed that 20% of the aggregated batteries capacity is sufficient to provide around 70-100% of each of the frequency reserves individually. The highest savings are gained for the households when both the primary frequency reserves, FCR-N and FCR-D, are provided by the aggregated batteries together with increasing the PV self-consumption, peak shaving and energy arbitrage. When providing frequency support the PV system payback time was reduced from 14 to 11 years when equipped with battery, compared to only installing PV.

1 Introduction

As more countries progress towards renewable energy, intermittency in the power system is causing an unreliable power supply. Flexibility solutions from prosumers, which both consume and produce electricity, is one solution to provide stability to the power system. Prosumers in the form of single- family houses with both PV and energy storage are studied in this paper.

With falling prices on decentralized technologies such as rooftop photovoltaics (PV) and energy storage, private consumers have gained an ever increasing interest in renewable energy and investing in local production, becoming so called prosumers who both consume and produce electricity. Studies have found that combining renewables and energy storage may offer the lowest cost power solutions in the future **[1]** **[2]**. Prosumers have the potential of greatly impacting the energy system as a whole and decentralised batteries can contribute significantly to lowering the need of transmission interconnections **[3]**.

In Sweden prosumers, defined as systems below 43,5 kW, account for 50% of total installed solar capacity. Battery attachment rates are a few percent but growing due to subsidies of up to 50% / 5000 EUR per installation. In Germany battery attachment rate for residential solar market was over 90% in 2019 **[4]** with total numbers now totalling 270 000 distributed battery systems installed at the end of 2020 **[5]**.

Li-ion batteries characteristics of having fast response times, high efficiency and high controllability makes them suitable for providing frequency regulation faster than other conventional methods such as hydropower **[6]**. As shown in this paper provision of frequency balancing services could provide significant income to prosumers with home batteries, if market access is possible. For comparison, the total installed battery storage capacity in Germany had at the end of 2020 reached 1400 MW, the bulk being residential, **[5]**. This is equivalent to total demand of Frequency Containment Reserves (FCR) on the largest market in Europe (Germany, Benelux, Switzerland) and half of the 3000 MW reference incident in the European synchronous area **[7]**. However, prosumer battery capacity is in Germany is still short of the frequency restoration reserve (aFRR plus mFRR) that totalled 7,2 GW in Germany in 2017 **[8]**.

Sweden has set national targets for 7-14 TWh electricity production from solar energy in 2040, equivalent to around 1000 W per capita or 5-10% of total electricity consumption [9]. This study uses for Sweden 1,7 GW distributed battery storage in 2040, compared to 9 TWh of annually stored energy (10-15 GW) included for 2050 for the 1000% renewable EU power system simulated in [3].

1.1 Balancing services in Sweden

This paper focuses specifically on the role of distributed prosumer storage for system balancing. The electricity grid has to constantly uphold a balance between the consumption and production of electricity. For deviations beyond 49.9-50.1 Hz the transmission system operator (TSO), Svenska kraftnät, buys regulating power as ancillary services from the balance responsible parties.

The regulating frequency reserves are divided into three levels, primary, secondary and tertiary reserves and vary with endurance and speed. The primary reserves are called fast frequency reserve (FFR) and Frequency Containment Reserves which in turn are divided into Normal and Disturbed (FCR-N and FCR-D). The primary reserves are the first to be activate during an imbalance, to make sure the frequency stays within the acceptable limit.

The secondary reserves consist of automatic Frequency Restoration Reserve (aFRR). Both primary and secondary reserves are activated automatically the tertiary, manual reserve, are called mFRR, and are activated to unload the aFRR and restore the frequency at 50 Hz. Other than the capacity renumeration, the reserves FCR-N and aFRR are also remunerated when their bid is activated. The amount of renumeration depends on the volume activated needed to restore the frequency. How the frequency deviates and is regulated by the reserves is shown in Fig. 1.

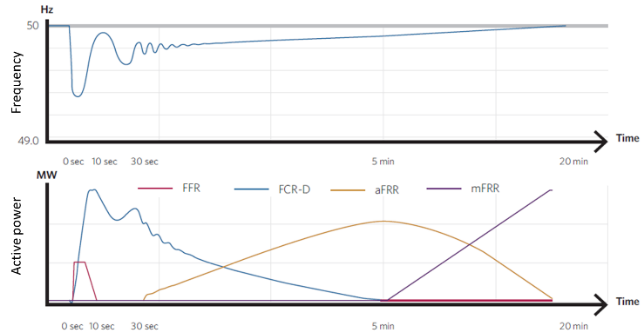


Fig. 1: Activation sequence of different ancillary services for balancing after an event (e.g. loss of production).

Table 1. Frequency reserves market characteristic

	FCR-N	FCR-D	aFRR	mFRR
Activation upon [Hz]	Frequency Deviation within 49.9-50.1	Frequency below 49.9 to 49.5	Deviation from 50 Hz remaining from FCR-N and/or FCR-D	Deviation from 49.90 – 50.1 Hz
Response time	63% within 60s + 100% within 3 min	50% within 5s and 100% within 30s	100% within 120s	100% within 15 min (longer time is allowed)
Time frame for bidding their capacity	One or two days prior to operation	One or two days prior to operation	Once weekly for the following week	From 14 days to 45 min prior to operating hour
Min required active time	1 hour	1 hour	1 hour (max 3 hours)	Deactivated end of hour or until notified by SvK
Activates	Automatic	Automatic	Automatic	Manually by SvK
Symmetric production (Up and/or Down)	Yes	No (only Up)	Yes (one direction at a time)	Yes
Min Bid size [MW]	0.1	0.1	5	10 (5 in SE4)
Required national capacity [MW]	227	427	150	Unlimited
Remuneration	Capacity: Pay as bid Energy: In accordance to price of upward and downward regulation	Capacity: Pay as bid	Capacity: Pay as bid. Energy: In accordance to price of upward and downward regulation	Energy: In accordance to price of upward and downward regulation

The automatic reserves were historically provided by hydropower and so requirements were made suitable for that technology. Currently the balancing markets and conditions are undergoing restructure to include other technologies such as distributed energy resources following the regulations given by the European Commission **[10]**. Characteristic of the various products (except FFR which was introduced in 2020) are provided in Table 1, with historical frequency reserve volumes provided in Table 2.

2. Methodology

The model seeks to minimize the cost of prosumer electricity consumption, which includes self-generation cost and the cost of electricity consumed from the grid. This was done by analysing the economic returns for homeowners made from using batteries for enhancing PV self-consumption, lowering network subscription fees (peak shaving), energy arbitrage as well as income from grid services in the form of frequency support. Each house is assumed to have a 10 kW PV capacity and a battery capacity of 6 kW / 7.68 kWh. The PV system size corresponds to average Swedish residential PV size in 2019 and the battery cost and details are those of the commercial offered storage solution of the studied retailer.

The number of households in Sweden that are assumed to install PV and battery systems is based on the target goal from the Swedish Energy Agency. It is assumed the prosumer share of total installed PV capacity is maintained at 50% throughout the studied period to 2040 and battery attachment rate of 50%. To meet national goal of 7-14 TWh electricity consumption from solar (5-10% of consumption) 300 000 houses (out of 2 million single-family houses) would have PV plus battery systems. Fig 2. shows the kW

Table 2. Frequency reserves volumes in 2018

	FCR-N	FCR-D	aFRR	mFRR
National required power [MW/h]	227	427	150	-
Net average activated volume Up [MWH/h]	53	0.21	71	180
Net average activated volume down [MWH/h]	58	-	82	207
Maximum activated volume in a single hour [MWh/h]	227	17	150	1495
Total activated hours Up [h]	3 802[2]	88[3]	3 870[4]	2 843[4]
Total activated hours Down [h]	4 477[2]	-	3 660[4]	4 046[4]
Total activated Up [GWh]	No data[5]	No data[5]	57.7	494
Total activated Down [GWh]	No data[5]	-	88.3	829
Activated volume renumeration [MSEK]	210	-	67	581
Capacity renumeration [MSEK]	790	705	128	-

energy flow for such a residential house with battery for a year.

Historic volumes and prices for Nordic balancing services (Frequency Containment Reserves: FCR-N and FCD-D as well as manual and automatic frequency Restoration Reserves: aFRR and mFRR) were used together with times series simulations of household load and PV production to assess the availability.

It was assumed that the PV installation rate of 2019 would continue with same annual volumes during 2020-2040, which would be sufficient to reach the national targets for 2040. Further, it was assumed that a proportion of the national installed PV capacity derived from the residential segment and a current average size of 8-10 kW per house was used. The total home battery capacity in 2040 was based on the assumed battery attachment rate of 50%, equivalent to the German proportion of PV systems with battery in 2018. This amounts to 1,68 GW / 2,13 GWh available battery capacity for balancing services in 2040.

All cost of PV system and batteries are based on 2019 commercial offering of PV and battery systems from costs from Vattenfall and its subsidies, including subsidies. More information on these assumptions are available in [11]. The homeowner's savings from reference services (self-consumption and peak shaving) was optimised using the software Homer Pro and balancing service provision income done with time-series studies on Microsoft Excel.

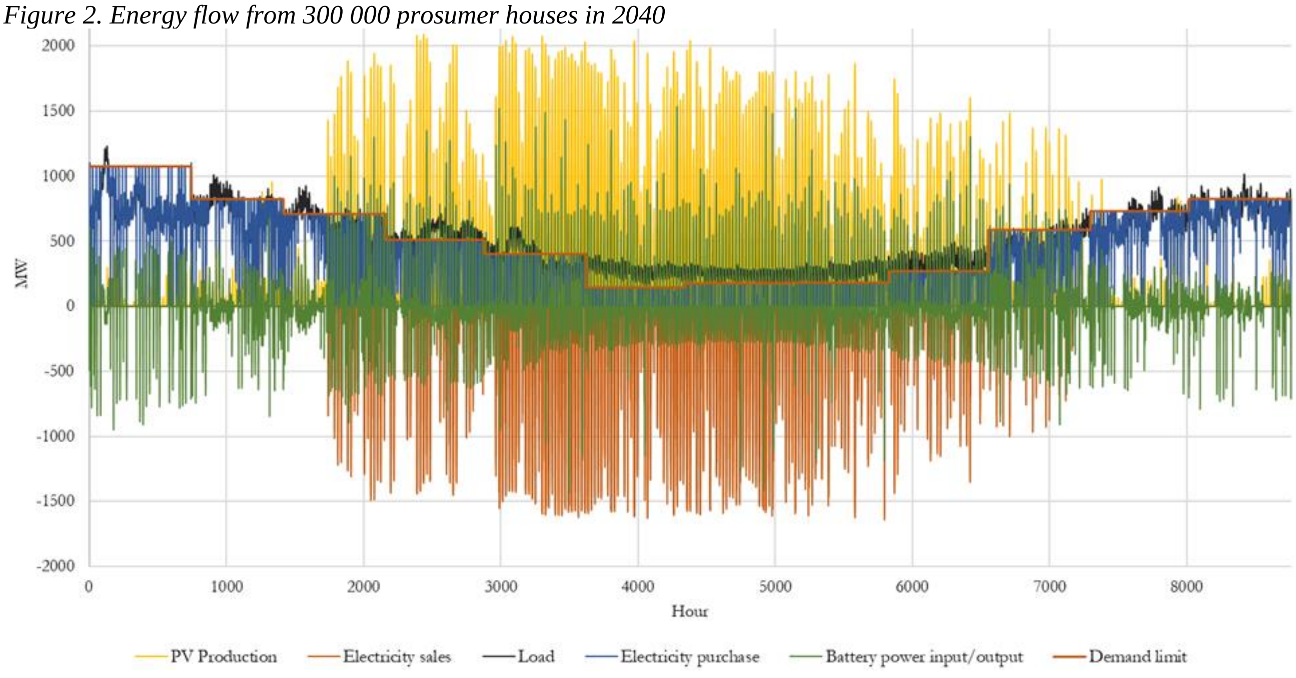
3 Results

The average of the load curves from all Vattenfall Distribution Sweden customers with a fuse level 20 A was taken to represent the national household's electricity consumption. Since this is an average load curve, the household's peaks are smoothed out by being aggregated with other houses. Production time-series was constructed as an average of 20 residential PV systems throughout Sweden. The resulting flow is shown in Fig. 2. However, to analyse the savings and costs for an individual household the load curve from one single family house was used. This is because the higher variation in the non-aggregated electricity consumption that each individual house has provides a more accurate image on what savings an individual household would have.

To assume what share of the aggregated battery's capacity would be used for frequency regulation, the national required balancing power is used. The highest requirement is for FCR-N, because it is symmetrical a need to either charge or discharge 227 MW during an hour is foreseen, requiring a total reserved capacity from the batteries of 454 MW per hour. It is assumed that each battery will provide the power/capacity ratio of 1 MW/MWh for frequency regulation. In order to provide 454 MW/MWh the aggregated batteries capacity amounts to around 21% of the total capacity of the batteries. The other reserves have smaller required capacity nationally as shown in Table 15, but in order to have as equal assumptions for all the reserves, the same capacity for each reserve is used. In order for each individual household to provide balancing as well as the household services from the battery, it is therefore assumed that around 80% of it is used for the household services and 20% is used for frequency reserves.

In the simulation 80% of the aggregated batteries capacity is used for the household's services and the energy flow During summer, the battery opts to charge as soon as there is excess PV production and discharge normally during the evening. During the winter season, the battery is mainly engaging in peak shaving and arbitrage due to the low solar production in winter at latitudes of 56 to 64 degrees of the

Figure 2. Energy flow from 300 000 prosumer houses in 2040



modelled PV system. The economic optimisation in Homer implies prosumers charge and discharge mainly to decrease the monthly peak power consumption.
For FCR-N, aFRR and mFRR the batteries provide both up and down regulation combined, therefore the initial SoC is set to 50%. Since FCR-D currently only regulates up, the SoC set to be 100%. The initial SOC for each reserve is shown in Table 3 below.

Table 3. Battery characteristics for providing frequency regulation

	FCR-N	FCR-D	aFRR	mFRR
Initial Soc	50%	100%	50%	50%
Recharge time [min]	6.8	13.6	6.8	6.8
Recharge hour	12:00	-	19:00	Every third hour

If every battery preserves 20% of their capacity, it is equal to 1.38 kWh for the individual battery. When providing both up and down regulation simultaneously each regulation's direction will have a capacity of around 0.7 kWh from each battery. Recharging the battery 0.7 kWh takes roughly 7 minutes and to 1.38 kWh around 14 minutes, based on the technical specifications of the modelled battery. The duration the battery can provide frequency regulation will depend on the volume activated and the SoC of the battery when frequency support was called upon.

On a national scale the results in table 4. show that 20% of the aggregated batteries capacity is sufficient to provide around 70-100% of each of the frequency reserves individually.

Table 4. Revenue and volume met by frequency regulation using 20% of prosumer battery capacity

	FCR-N	FCR-D	aFRR	mFRR
Energy [MSEK]	168	-	49	182
Capacity [MSEK]	622	705	121	-
Total [MSEK]	**791**	**705**	**170**	**182**
Historical volume met in 2018 [%]	80%	100%	68%	32%

From the results in table 4, FCR-N gives the highest revenue for the battery with FCR-D bringing the second highest revenue. The revenue for providing these ancillary services is recalculated per prosumer and compared to the use case of households with solely a grid connection and with only PV installed in table 5.

Table 5. Energy analysis

	Drawn from Grid [GWh]	Fed to grid [GWh]	Total transmission [GWh]	Transmission change [%]	PV Self-consumption [%]	Self-sufficiency [%]
Grid scenario	4 314	-	4 313	-	-	-
PV scenario	3 264	1 569	4 834	10.7	40	24.4
PV + Battery	2 934	1 229	4 163	-3.6%	53.8	32.7

Historically, FCR-D is activated very seldom and with small volumes, therefore a combination of providing both FCR-N and FCR-D was found to maximize the revenue generated by the decentralized batteries. 80% of the battery's capacity would be sufficient to meet both the household services and at times, the FCR-D when used. The remaining 20% is only used for FCR-N so that it is always available.

As shown in table 6 the payback time of the scenarios is the least with the addition of a battery used for both primary reserves and the household services, the simple payback time is around 9 years and the discounted payback time is around 11 years compared to 14 years without provision of balancing services and savings made from the battery services.

Table 6. Economic analysis for with 20% of prosumer battery's capacity for frequency regulation

	Electricity charge savings	Peak shaving savings [SEK]	Annual frequency regulation revenue [SEK]	Annual savings + revenue [KSEK]	Simple payback time [yr]	NPC [kSEK]	Discounted payback time [yr]
Only grid	-	-	-	-	-	257	-
PV scenario	11 733	142	0	11 874	12.3	221	14.2
PV + Battery IEPF scenario (FCR-N)	12 115	1 623	2 563[6]	16 301	10.5	194	12.8
PV + Battery IEPF scenario (FCR-N + FCR-D)	12 115	1 623	4 846[7]	18 584	9.2	167	11

Between the PV and the battery, the implementation of household batteries is still in maturing phase. Therefore, the sensitivity analysis in Fig. 3 was performed to pinpoint which of the costs related to the battery's payback time that are the most influential to prosumer profitability.

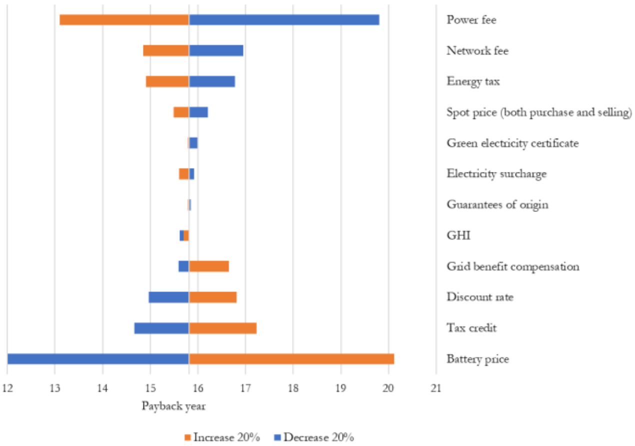


Fig 3. Sensitivity analysis for the discounted payback time of the battery

The sensitivity analysis is done for the single family house where the PV and battery's discounted payback time was around 15.8 years in lieu of income from balancing services. Each cost is increased and decreased with 20% while all other costs are kept the same. The battery price and the power fee from the grid operator are the most impactful factors to the battery's payback time. Further details of the study together with sensitivity analysis can be found in **[11]**.

4 Discussion

For the household batteries to provide balancing of the grid system, one limitation is the bidding market for frequency regulation. The reserve market closes at earliest one day ahead of activation for the automatic reserves, this makes it difficult to predict the household's electricity consumption and PV production for the next day accurately before the bidding period is finished. For the batteries to participate in the frequency regulation market, the bidding period will have to become much shorter. Also, the minimum bid size for each reserve which is at least 0.1 MW also makes it difficult for DER to participate in this market unless they are aggregated. SvK also admits to the market needing a transformation to promote prosumers participation [10].

This study partitioned the prosumers batteries with 80% of storage capacity used to optimise PV self-consumption, peak shaving, energy arbitrage at the day-ahead electricity market and FCR-D with remaining 20% dedicated to FCR-N. Although it is recognised that an optimisation of entire battery capacity could meet a larger need of balancing services. The view of the authors is that a dedicated partition of the batteries will simplify pre-qualification towards TSO as it guarantees an available capacity.

5 Conclusion

When providing frequency support the prosumer PV system payback time was reduced from 14 to 11 years when equipped with battery, compared to only installing PV. In the study the highest savings are gained for prosumers with PV and battery storage systems when primary frequency reserves, FCR-N and FCR-D, are provided by 20% of the aggregated batteries capacity and the remaining 80% providing household services of increasing the PV self-consumption, peak shaving and energy arbitrage. Based on national targets for solar PV production in 2040 it was found that 20% of prosumer batteries capacity reserved for frequency reserves could meet 100% of today's FCR-D. needs, 80% of FCR-N and 68% of aFRR. However, Manual Frequency Restoration Reserves, mFRR. would be met only to 32%, unless a higher proportion of battery capacity is utilised.

It was found that income from using 20% of battery capacity for balancing services would over 15 years be equivalent to the 60% investment subsidy for home energy systems available in 2020 (subsidy was reduced to 50% in 2021). Results show that a non-subsidised prosumer PV system together with a battery would prove more cost efficient than a PV system alone, if prosumers have access to the national balancing markets. This implies that the current battery investment subsidies could be replaced by TSO frequency support payment, meaning that batteries could be rolled out with no additional cost to tax payers.

The study did not simulate the effect of prosumer batteries on future regulation prices and volumes. TSO balancing cost are past directly on to consumers. If increased competing on balancing markets could help to counter the recent years increasing balancing costs in Sweden the proposed financing scheme could lower the total cost of electricity for all users, thereby sharing the economic benefits of prosumer batteries to more than owners of the PV battery systems.

5 Acknowledgements

This paper is based on a Master of Science thesis made at Vattenfall R&D for Vattenfall solar PV sales organisation. The full thesis **[11]** also studies increasing PV self-consumption, peak shaving, energy arbitrage at the day-ahead electricity market as well as the described service of providing the frequency services in this paper.

6 References

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