Assessment of Grid-connected Residential PV-Battery Systems in Sweden - A Techno-economic Perspective

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Abstract—**Ensuring a secure supply of electricity without harming climate is a key challenge for future power system and many renewables-based cutting-edge technologies are introduced to overcome this challenge. This paper aims to study the grid-connected residential PV-battery system at behind-the-meter scenarios in Sweden from a technical and economic perspective. The system is designed with PV arrays, inverters, Lithium-ion or lead-acid batteries. The optimal PV, lithium-ion and lead-acid battery size are determined at two locations (Arlanda and Karlstad) in Sweden based on the highest value of Net Present Value (NPV), Profitability Index (PI), the lowest value of Levelized cost of energy (LCOE) and payback period considering system losses, electricity market price, cost and PV incentives and a comparison is performed between these two locations against some techno-economic performance metrics for two combinations of PV-battery systems. Then, the best-case energy profile, bill savings, battery performance are also investigated. Finally, the system is simulated using System Advisory Model (SAM), a renewable analysis software from NREL, USA, and is found that the grid-connected PV with lithium-ion battery system is feasible and more economical considering available PV incentives in Sweden.**

Keywords—Solar PV, Behind-the-meter, Battery, NPV, Residential load

I. INTRODUCTION

Electricity is considered the world's fastest-growing form of energy consumption and the global electricity demand has skyrocketed in recent times due to technological advancements and population growth [1]. Nonetheless, the global power system is confronted with two main challenges; providing a sustainable supply of electricity and mitigating environmental impact caused by fossil-based power generation [2]. As of today, around 85% of greenhouse gases have emitted from fossil fuels such as oil, natural gas and coal which are the main source for electricity production [3]. Therefore, the conventional power grid needs to integrate with up-to-date energy technologies to overcome these challenges. Nowadays, the proliferation of distributed energy generation (DER) technologies are strengthening as an alternative energy solution with consistent development in storage technology [4].

Among all other renewable sources, solar PV technology is well-known for its abundant energy in form of sunlight, module efficiency and eco-friendliness [5]. However, higher capital investment is considered as a major constraint for PV system implementation in many countries [6]. The cost-effectiveness of a distributed PV system has increased when several demand-side management (DSM) techniques such as demand response, peak load shaving are integrated [7] and thus, the PV system lifetime, Levelized Cost of Energy (LCOE) are expected to enhance by 2025 [8]. In consequence, a comprehensive technical and economic assessment of the PV-battery system can increase the number of energy prosumers at the distribution side in a behind-the-meter approach by quantifying the system's profitability. The term "behind-the-meter" means the distributed renewable energy generation facility at customer premises. In this approach, the end-user will get the opportunity to be a prosumer and able to integrate the rooftop PV system, battery storage and DSM techniques at the distribution side.

In this paper, we aim to evaluate the technical and economic performance of a grid-connected residential PV-battery system in a behind-the-meter approach in Sweden. Accordingly, two combinations of the PV-battery system are investigated for the selected locations in Sweden. The locations are selected based on the higher solar irradiance profile and availability of the aggregated one-year residential load data for fifty apartments. Then, a PV-battery system is designed comprising PV modules, inverters, lithium-ion and lead-acid batteries. For economic analysis, eight price scenarios are formed from Nord-Pool electricity market price data with system cost and PV incentives. Afterward, the optimum PV-battery system is determined based on the system's Levelized Cost of Energy (LCOE), Net Present Value (NPV) and profitability index (PI). Finally, the best-case is further investigated to determine the system lifetime energy profile, electricity bill saving, battery performance and peak shaving potential. The system is designed using the System Advisory Model (SAM), a simulation software from NREL.

Sweden has profoundly aligned with the European Union (EU) energy policy to produce 100% energy from renewable sources by 2040 and improving 50% energy efficiency by 2030 [9]. In 2019, almost 58% of electricity in Sweden produces from renewable sources. But, the contribution from solar technologies is found only 0.12% in a total of 161.2 TWh electricity generation. In opposite, the grid-connected solar PV production is 67% in 2018 with a current capacity of 411 MW. Nevertheless, around 50% of the total electricity is consumed by the residential and service sector. Hence, the grid-connected PV based technology is well thought-out as a sustainable solution for Sweden [9].

However, the PV system techno-economic assessment results vary based on geographical location, load data, electricity pricing, and system cost. Any inclusive technical and economic studies on the PV-battery system will help to achieve the Swedish energy goal of 100% renewable energy production. Nevertheless, no PV-battery system case study is found considering all techno-economic parameters at Arlanda and Karlstad, Sweden according to the author's knowledge. Thus, the outcome of this study will help policymakers and investors in Sweden to design the future residential grid-connected PV-battery system in a behind-the-meter approach in a more economical way.

In this paper, section II covers the contemporary study on PV and battery systems and section III discusses the PV system technical and economical design methods. The results are presented in section IV and discussed in section V. The study is concluded with several implications and recommendations for future work in section VI.

II. Background Study

The studies on grid-connected residential PV system at different geographical location produces diversified performance results. A case study at Kyushu, Japan illustrates that a residential PV system can share a 2% load from the national grid and able to reduce 1.1% of peak load at 18 years payback time [10]. In a study on Australian agent-based household PV-battery system, PV 15% self-consumption increased after combining battery storage [11]. For economic assessment, the PV system with different residential feed-in-tariff schemes is expected to increase grid energy export seven times from PV by next the 20 years in Australia [12]. Similarly, the residential PV-self consumption with battery system is expected to be fully profitable by 2030 in France [13]. The study of PV system economic analysis at Texas state university, USA also implies that 17% annual cost can be saved if the PV system is installed at 13 on-campus buildings with an annual production of 15391 MWh [14]. Besides, a study on the policy coordination model on the German grid suggests that storage incentive and maximum grid feed limit reduces the stress on the distribution grid and creates a balance between self-consumption and feed-in-grid [15]. Moreover, a Study in Thailand investigates the return to residential customers using PV-battery systems under decreasing battery prices based on net present values (NPV) and Levelized Costs of Energy (LCOE) and shows that the battery size and it's cost and retail rate design has a substantial impact on the return [16].

To assess the residential PV-battery systems, several case studies are conducted in Sweden. An investigation on the transformation of Swedish residential consumers into prosumer is conducted at the building cluster level shows that, 77% of PV self-consumption rate increases by the couple PV system [17]. Similarly, PV self-consumption rate was increased up to 17% in Landskrona, Sweden when the system is assessed without battery [18]. In another case study in Eskeltuna, Sweden presents an aggregator-based business model for residential PV system found that peak shaving earning is profitable for the new aggregator [19]. Then, the economic assessment at 615 sq. meter PV array size in Ludvika, Sweden found 27,394 kWh annual energy and 10 years of the payback period for mixed tariff and self-consumption mode [20].

III. PV System Design Methods

A. Solar Irradiance Profile

The solar irradiation profile is assessed in SAM at five locations in Sweden. Out of these locations, maximum annual energy yields 988 kWh/kW and 914 kWh/kW is measured at Arlanda (59.65°N, 17.95°E) and Karlstad (59.37°N, 13.47°E) respectively with 6.5 ºC and 5.9 ºC average temperature.

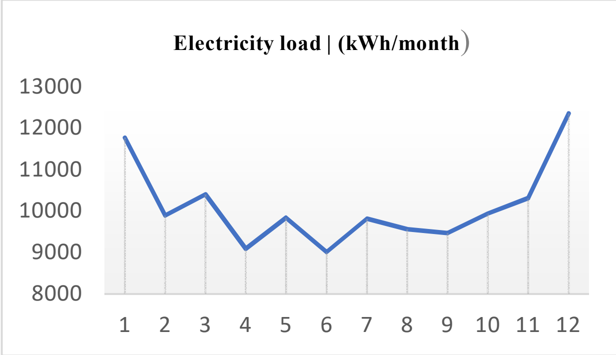

Fig. 1. Monthly load profile of Year (1)

However, the total amount of radiation, received by the system array known as global horizontal irradiance (GHI) is found to a maximum of 781 W/m2 and average 114 W/m^2 in Sweden. The average value of GHI is quite low in Sweden in comparison with other European countries [19] due to significant irradiance variation between summer and winter. The solar resource data is taken from the SAM library originated from ASHRAE International Weather for Energy Calculations Version 1.1 (IWEC). [21]

B. Aggregated Residential Load

The hourly one-year load data (collected from local DSO) of fifty small apartments are aggregated as a single DSO meter (50 A fuse size) in a behind-the-meter solution. The total annual energy consumption is 121 MWh with a peak demand of 33 kW in December. Fig.1 shows the monthly energy profile for a year. The maximum energy is consumed in winter (November-January) for the additional heating load and less energy is consumed in summer (April-August).

C. PV-Battery System Design

To design the PV system, the sun power SPR315-E module and ABB-PVI-6000-277V inverter are used from the SAM database. The maximum power capacity of the module is 315 W (dc) at STC (total irradiance 1000 W/m^2, temperature 25 ºC and air mass 1.5) with an efficiency of 19.3% [22]. The PV array is composed of single-crystal silicon cells and requires only 1.63 m^2 for each cell. In this system, the optimum DC-AC ratio is calculated as 0.95 for the selected module and inverter and the fixed PV array tracking mode is used with 44° tilt and 182° azimuths. After that, the overall 15.22% system loss of annual production is considered which is composed of 5% irradiance loss, 4.5% DC loss and external shading loss, 2% net AC loss and 1% maintenance loss [23].

The PV module degradation rate is set at 0.5% at 25 years analysis period [24].In the battery system design, the lead-acid VRLA and the lithium-ion NCA batteries are selected [25] .The lead-acid battery's capacity is faded just after 1200 cycles when the depth of discharge rate is 30%, whereas the lithium-ion is faded at 5000 cycles in 20% depth of discharge. The minimum and maximum state of charge (SoC) limit is set from 30% to 90%. SAM algorithm computes the stored battery energy and compares it with the load and PV production in each time step. If PV production is greater than load then, the battery charges from PV and if not fully charged then, it takes power from the grid to be fully charged. If PV production is less than load, the battery discharges power to meet the load. In all cases, the grid power is the last option to meet the load and battery charging [25].

D. Electricity Market Price Analysis

To analyze the dynamic pricing of the electricity market, the hourly one-year spot price data is taken from the Nord-pool spot market (NPSM). Then, the spot-price is categorized between summer (May-Oct) and winter (Nov-April). After that, the seasonal categories are further classified as weekdays- weekends and peak-off peak hours to observe the real price impact in each time period. To assess the energy price, the spot market price is varied from 0.18 SEK/kWh to 0.32 SEK/kWh at eight time periods. To design the retail price, all input prices are averaged for all time periods after evaluating the price schemes and contracts of two large DSO (E. ON and Vattenfall) in Sweden. The retail price is fixed at 0.35 SEK along with the energy tax of 0.29 SEK and green certificate price of 0.26 SEK. For grid price estimation, the average grid connection tariff of 50A fuse is found as 16040 SEK/year after evaluating the DSO pricelist. Normally, the grid fee is composed of an annual connection fee depends on fuse rating and grid transfer fee. The net metering option in SAM implies that surplus PV electricity will be sold to the grid at a selling price of 0.29 SEK/kWh which is the grid sell back price in Sweden. In this case, SAM compares the system load and PV production in each hour and decides on buying or selling electricity from or to the grid [26].

E. PV Incentives and Financial Metrics

Three incentives from the Swedish government are considered for this study. First, Investment tax credit (ITC) refers to the tax exemption for the integration of renewable energy into the grid. The maximum integration value for a single DSO connection point is 30 MWh and the tax exemption value is 0.6 SEK/kWh. Then, the production-based incentive (PBI) refers to the participation in the green certificate market and the value is 0.196 SEK/kWh. Finally, direct investment sharing which is 30% of the total installed cost. To design the financial parameters for the Swedish market, the debt ratio is selected as 100% and the inflation rate 2% to calculate the system cost and project cash flow for the total analysis period. The discount rate for solar PV projects usually varies from 5% to 9%. Thus. the discount rate is set to 4% due to low investment risk in Sweden. Later, the project salvage value is selected as 10% of the total installed cost that is appeared at end of the project cash flow analysis. Finally, a 30% sales tax is fixed according to Swedish tax law [26].

F. Estimation of System Cost

The PV module price is considered as 6.2 SEK/W(dc), inverter cost 1.7 SEK/W(dc), the balance of system (BOS) cost at 1.65 SEK/Wdc, average installation labour cost 2.48 SEK/W (dc) with an installer profit margin of 2.42 SEK/W(dc). Then, the engineering cost is taken as 1 SEK/W (dc) and 25% VAT is added on top of all the costs except engineering, according to Swedish tax law [26]. Finally, the operational cost is considered as 1.5% of the total installed cost per year. To design the battery cost, a capital investment of 2550 SEK/kWh for the lithium-ion and 3828 SEK/kWh for the lead-acid battery is considered [27].

IV. Result

To obtain the optimum PV and battery size, the system size has varied from 30 kWp to 60 kWp for PV and 3 kWh to 40 kWh for the battery. After multiple simulations, the maximum NPV and minimum payback period is found at 40 kWp PV and 3 kWh battery size for both systems with lithium-ion and lead-acid battery at Arlanda and Karlstad. Then, four cases are designed at two locations. Table I presents the technical and economic output of both systems. For system technical metrics, the capacity factor is the ratio of annual ac energy delivered to the system and the maximum capacity of annual energy production founds maximum 11.3% for the PV systems with lithium-ion batteries in Karlstad. Thus, the highest annual energy output of 39,223 kWh is found for PV system with lithium-ion batteries at Karlstad when the energy yield is 988 kWh/Kw. For all four cases, 78% performance ratio is found because of the same system loss profile. In comparison with Lithium-ion and lead-acid battery, lead-acid battery shows the lower efficiency of 61.8% and thus the storage capacity is reduced.

To assess the system economic parameters, the ratio of total system lifetime cost and the annual energy production known as the system levelized cost of energy (LCOE) is calculated lowest 0.95 SEK/kWh for the PV-lithium-ion battery system at Karlstad. In opposite, the system with the lead-acid battery at Arlanda shows a maximum LCOE of 1.11 SEK/kWh. The Net Present Value (NPV) of four cases shows that, the highest NPV 127 kSEK is found for the PV system with lithium-ion battery at Karlstad with a payback period of 10.8 years whereas the lowest NPV 41.5 kSEK at 12.5 years'

TABLE I. COMPARISON OF PV SYSTEM PERFORMANCE PARAMETER

Performance Parameter	**PV System at Karlstad**		**PV System at Arlanda**	
	PV lithium-ion	***PV lead-acid***	***PV lithium ion***	***PV lead-acid***
Annual energy (kWh)	39223	39080	35026	34905
Capacity factor	11.3%	11.2%	10.1%	10%
Energy yield (kWh/kW)	988	984	882	879
Battery efficiency	97.5%	62.2%	97.7%	61.8%
Levelized COE (SEK/kWh)	0.95	0.97	1.09	1.11
Net present value (kSEK)	127	112	55.7	41.5
Payback period (years)	10.8	11.1	12.1	12.5
Profitability index (PI)	23.9%	21.1%	11%	8%

TABLE II. SYSTEM ENERGY PROFILE

Energy Metrics	**Year 1 (MWh)**	**Year 25 (MWh)**
Load	121	3037
System energy	39	923
Load from PV	29.4	723.2
Load from Battery	0.6	6.8
Load from grid	91	2307
Export to load	9	197
Import from grid	91	2311

payback period is calculated at a system with lead acid battery at Arlanda. Finally, the system with lithium-ion battery at Karlstad shows the highest profitability index (PI) of 23.9% whereas the lowest 8% is found for a system with lead-acid battery at Arlanda. It is observed that PV system with lithium-ion battery at Karlstad is considered as the most economical solution based on the highest NPV (127 kSEK) and PI (23.9%) and lowest LCOE (0.95 SEK/kWh) and payback year (10.8 years) in comparison with other three cases. The best-case system energy profile, bill saving, battery performance and peak shaving potential are presented below.

A. System Energy Profile

The system's annual energy production decreased each year due to the 0.5% module degradation and thus the annual energy imports from the grid increase from the first year to the end of the analysis period. Table II represents the system energy consumption profile from the PV system and grid. A total of 25% demand is met by the PV with lithium-ion battery system in the first year and it continues close to this value reaching 24% at the end of the project lifetime.

B. Estimation of System Bill Saving

The annual bill saving for the system with the Lithium-ion battery at Karlstad is 46.2 kSEK. Fig.2 shows the maximum 20 kSEK electricity bills in December and the minimum 14 kSEK in June without any system. Therefore, the monthly average bill is reduced from 16 kSEK to 12 kSEK after installing PV and battery system

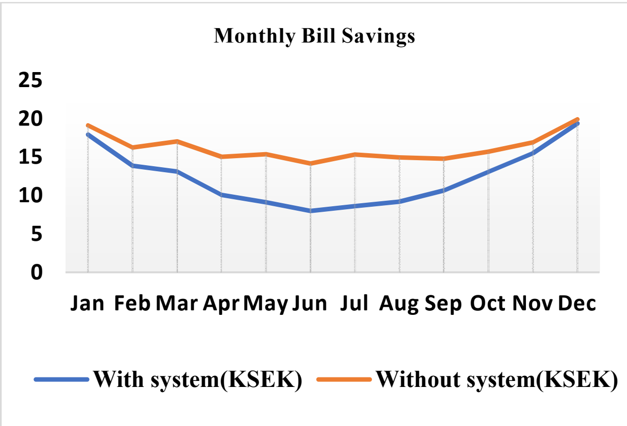

Fig. 2. Monthly electricity bill saving

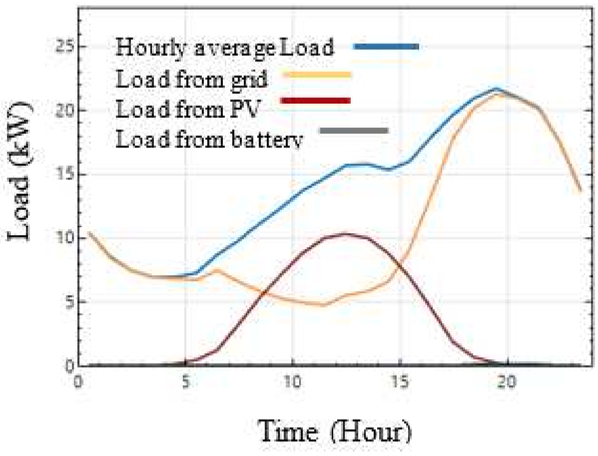

Fig. 3. System peak shaving

C. Evaluation of Battery Performance

The charging and discharging efficiency of lithium-ion batteries are found as 97.1%. A total 6757 kWh energy is taken for battery charging and 53% comes from the PV production in the lifetime. A total of 3450 cycles is found during a lifetime at 56.4% depth of discharge (DoD) and 67.7% of average capacity degradation. The total lifetime charging capacity is 800 kWh at the first year which drops to 380 kWh at the end of the period due to capacity fading.

D. System Peak Shaving

Fig.3 shows the average hourly peak power consumption at the time between 18:00 pm to 22:00 pm in a day. In the optimum sizing, peak power consumption is between 18:00 pm to 22:00 pm is reduced by 1 kW (4.5% of peak load) when the battery storage is used.

V. Discussion

The optimum PV and battery system size is determined as 40 kWp PV and 3 kWh Li-ion battery in Karlstad, Sweden for 121 MWh aggregated residential load in behind-the-meter approach. The capacity factor at the Karlstad system is 11.3% with annual PV production of 39.23 MWh and 10.1% for the Arlanda system with annual PV production of 35.02 MWh. Although, the distance between Arlanda and Karlstad is 300 km, but the annual production and system profitability index intensely varies with a 1.2% difference in capacity factor. In context, the NPV at Karlstad (127 kSEK) is found higher than the Arlanda system (55 kSEK). The results show the importance of location selection for the PV-battery system. Then, the performance ratio is found 0.78 for all four cases as the same system loss value is used. A similar study on PV performance in the island of Crete, Greece found a performance ratio range 0.58 – 0.73 with an average of 0.67 [24].

In many other PV based grid-connected residential study, Net present cost (NPC) and LCOE are consider as a key performance parameter. For example, a study on grid connected PV systems at five climate zones in china found the least NPC ($11282) and Cost of Energy (COE 0.073$/kWh) in Kunming as the most economical system [28]. In a similar case study in Iraq, grid to charge configuration is found most economical at NPC ($11282) [29].In this paper, the highest NPV (127 kSEK) and PI (23.9%) and lowest LCOE (0.95 SEK/kWh) is found for the system at Karlstad (40 kWp PV and 3 kWh battery size) in comparison with Arlanda. The economic metric NPV denotes the overall net cash flow of the system which includes the system net income from bill saving and grid sell-back in the calculation providing the more robust result in techno-economic analysis. [30]. In another context, the nationwide economic feasibility at nine provinces in Turkey found the pay-back period of 7-14 years. [31]. Similarly, PV system studies in South Africa found 2-3 years payback period and a high capacity factor (17%-18%) [32]. In our case, the payback period is found 10.5 years for best-case considering PV incentives and grid sell-back price at 0.29 SEK/kWh.

In opposite, the study in Northwest China illustrates that the grid connected PV-battery system is found uneconomical at five locations [33]. In a similar case study in New Delhi, India, the LCOE is increased with the increment of battery capacity which makes grid-connected PV battery unprofitable

[34]. A case study in Oman demonstrates that the grid connected PV system can only be achievable if the residential electricity price is high and battery cost can be reduced[35]. Besides, the grid-connected residential case study in Surabaya, Indonesia founds the system uneconomical with 17.5 years of payback time without any government incentives. But shows the improved result of 6.5 years payback time after adding 0.25 $/kWh feed-in tariff price [6].

In this paper, the PV system with a battery (though the battery optimum size is small) in Sweden is found economically competent only when the current PV incentive is considered. This study is conducted by considering currently available three different Swedish PV incentives where 30% of capital investment makes the system economically feasible. In contrast, the result of the system economic performance without any government PV incentives shows negative NPV (-225 kSEK) and profitability index (PI) is -0.296 without current incentives for 40kWp PV and 3kWh battery system at Karlstad, Sweden.

The further energy profile analysis of PV system with Lithium-ion battery at Karlstad shows that, the system can reduce 24% grid load and can import 21% to grid which is significant for PV-battery size and seasonal-peak relationship as the peak load in Sweden is found in winter and maximum PV produced in summer. A total of 9 MW is exported to the grid in the first year and ends at 197 MW after 25 years of the analysis period. Therefore, the overall electricity bill is reduced to 155 kSEK from 192 kSEK. The revenue is calculated from annual bill saving and grid feed-in-tariff price. It is noticeable, the electricity price trend in Sweden is found downward in last five years for residential consumers which increases the PV system business risk factor. In battery performance assessment, Lithium-ion battery efficiency is significantly higher (97.1%) in comparison with lead-acid battery (62.1%). A comparative study among lithium type (LCO, LCO-NMC and LFP) and the lead-acid battery showed the better efficiency and power performance of lithium type battery and recommended for renewable application. To observe the peak shaving capacity, at the optimum battery size (3 kWh) peak power consumption is reduced by 1 kW (4.5% of peak load). The peak reduction capacity depends on the size of the battery. A study on PV peak shaving capacity analysis in Shanghai, China illustrates that, Levelized Cost of Energy (LCOE) increases if higher battery capacity is used and thus system profitability is reduced.[36].

VI. Conclusion

The paper aims to determine the optimum PV-battery sizes and assess the techno-economic performance of the system in behind-the-meter for aggregated residential load in Sweden. The designed PV-Battery system is analyzed by two combinations of PV and Battery systems at two locations (Karlstad and Arlanda) in Sweden. The optimum size system 40 kWp PV and 3 kWh Lithium-ion battery is determined at Karlstad corresponding to lowest LCOE (0.95 SEK/kWh) and payback period 10.5 years and highest NPV (127 kSEK) and 23.9% profitability index (PI). Finally, The PV- Lithium-ion battery system is found economically feasible at Karlstad Sweden if only the current incentives from the Swedish government are considered.

The future study on PV-battery system in a behind-the-meter model can be composed of inclusion of other revenue-generating assessment to provide better economic result without any subsidy/incentive. Then, the impact of dynamic pricing of electricity market, multiple feed-in-tariff options and residential load scaling can be investigated. The commercial and industrial load profile can be investigated with different end-consumer price schemes which might enhance the PV-battery system growth. Finally, the results of this study will help to evaluate the technical and economic performance of PV-Battery system at the same kind of weather profile, load, and tariff structure in Sweden.

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