Role of Solar PV Prosumers in Enabling the Energy Transition Towards a Fully Renewables Based Power System for India

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Abstract – **Globally, PV prosumers account for a significant share of global solar PV capacity and a continuing trend with ever increasing retail electricity rates, as well as performance improvements of solar PV and innovations that allow for greater consumer choice, with additional benefits such as cost reductions and availability of incentives. This paper presents least cost options for Indian PV prosumers with battery storage and electric vehicle until 2050, and the long-term role of these PV prosumers in achieving a fully sustainable energy system, in the process stabilising the distribution grid network while ensuring availability of low cost solar power during peak demand periods.**

Keywords – Solar PV; Prosumers; India; Electric vehicles; Storage; Battery; Grid integration

I. INTRODUCTION

There is an increasing emphasis on the development of solar energy, predominantly solar photovoltaics (PV) in India for a variety of reasons, including the limited availability of conventional energy resources, their substantial environmental and social impacts, enabling energy access, rapidly declining costs and the global commitment in tackling climate change. In this context, the government of India has set out ambitious plans of increasing shares of renewable energy in the country's installed energy mix to 175 GW by 2022 and around 350 GW by 2031 [1]. The government has revised its solar energy target to 100 GW of installed solar power capacity until 2022 [2] and further up to 250 GW by 2030 [1]. The recent trends validate initiatives taken by the government to harness the massive solar potential in the country with installed capacity reaching 13 GW, as of June 2017 [3]. This national target has direct and significant implications for the residential sector as 40 GW is expected to come from rooftop solar PV systems across the country [4].

Globally, residential prosumers account for a significant share of global PV capacity. Estimates showed that in 2013, between 25-35% of the global cumulative installed capacity of PV was owned by residential entities [5]. Rooftop solar PV installations in 2016 had a share of 25-30% of the total solar PV installed around the world [6]. In India, the total installed rooftop solar PV capacity is estimated at 1,247 MW as of end 2016 [7]. It has maintained a 10-12% share of overall solar capacity, which is much lower than other key markets such as US, Germany, China, Spain and Australia, where the rooftop PV ratios can go up to 90% [8][7][6]. But, rooftop solar PV with the options that allow consumers to generate electricity at the point of consumption, and send any excess into the grid, are emerging as an attractive option for Indian households as well as households around the world.

These developments create a conducive setting for the development and growth of electricity prosumers in the Indian context. Prosumers are end-use consumers of electricity who also produce their own electricity at the point of consumption to meet their own electricity needs, to export electricity to "the grid" (the electricity system), or some combination of both. Simply, prosumers are electricity consumers interacting with the grid by generating some amount of electricity [9]. The increasing number of prosumers could transform the electricity system and the way in which all electricity consumers interact with it. This is happening in a number of countries such as, Australia, Chile, Germany and many of the EU countries, that are promoting policies for enhanced self-consumption through residential PV installation [10]. In addition to the ability of prosumers to self-generate and connect with the grid, prosumers have the potential to help mitigate the growth of energy supply-demand gaps and electricity system losses. These potential benefits are particularly important at the city level, where almost two-thirds of the world's energy is consumed and where consumption is set to rise with rapid rates of urbanization globally [11].

The major policies that enable development of prosumers are net-metering and feed-in tariffs. Net-metering allows customers (residential, commercial and industrial) who generate their own electricity from solar power to feed electricity they do not utilise into the grid [10] [12]. Net-metering acts as a billing mechanism that credits electricity customers that are solar energy system owners for the electricity they add to the grid. For example, if residential customers have a solar PV system on their rooftop, it may generate more or less electricity than utilised by the customer. At the end of a billing cycle, customers are invoiced with a single financial transaction and are only billed for their net energy use (energy consumed minus energy fed into the grid) [12]. Feed-in tariffs provide an incentive for customers to feed the excess generation from solar PV to the grid and hence lower their energy bills. In India, 29 states and 7 union territories have notified grid connectivity regulations with provision for net/gross metering and additional subsidies for rooftop solar are in place [13]. Not much used is the net billing option that allows sharing the benefits of low cost solar PV amongst prosumers, utility and the state in a fair way [14].

The development of storage technologies, more precisely battery storage (Lithium based batteries) have enabled prosumers to increase self-consumption of solar PV generation and further reduce energy costs. The market for rooftop solar-plus-storage systems took off in 2016, especially in Australia where an estimated 5% of new solar rooftop installations included storage, amounting to 6,750 battery installations (52 MWh), up from 500 in 2015 [6]. In countries with high retail electricity prices, rooftop solar-plus-storage systems are increasingly becoming the cost effective option and enabling consumers to turn into prosumers. And in India, with storage becoming an attractive option the adoption rate is expected to increase by 20% and reach potential installations of 25 GW by 2024-25 [15].

Driving the demand and contributing to the declining costs of batteries is the increasing adoption of electric vehicles (EVs). In 2016, global sales of EVs reached an estimated 775,000 units, representing around 1% of global passenger car sales, and more than 2 million passenger EVs were on the world's roads by the end of 2016 [6]. Taking cue from this global developing trend, the Indian government has laid out ambitious plans for the promotion and adoption of electric vehicles with 6-7 million targeted by 2020 and to have an all cars sold by 2030 to be electric [16][17]. With the rapidly declining costs of both solar PV and batteries there will be an increasing number of prosumers with solar PV, battery storage and electric vehicles in the near future. In this regard, the research paper explores the possible development of PV prosumers in the Indian context and determines the least cost option for PV prosumers in the future up to the year 2050 with 2 scenarios of a prosumer with an electric vehicle and without an electric vehicle.

The research findings are presented as follows: the section II, outlays the methodology, the input data and the approach used for simulating a prosumer. This is followed by the assumptions and the description of the two scenarios used for the estimation of least cost configuration of the systems. In section V the results are showcased followed with discussions. In the final section VI, conclusions and challenges for the future are discussed.

II. METHODOLOGY AND INPUT DATA

Firstly, an Indian prosumer is considered to be an average Indian household with the capability of installing solar PV, a lithium-ion battery storage and owning an EV as shown in Fig. 1.

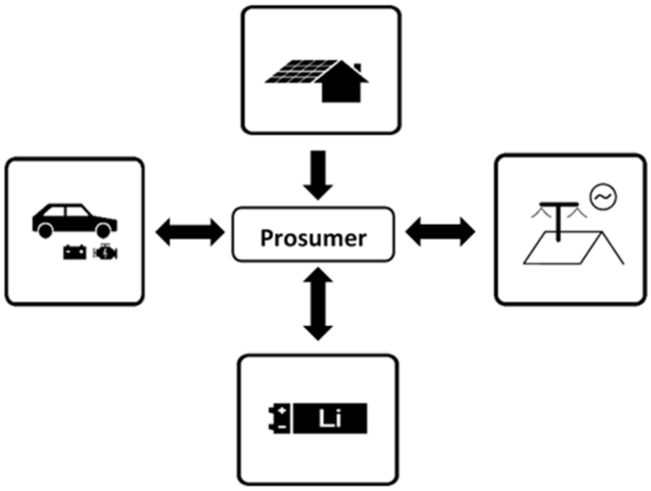

Figure 1. Schematic of a Prosumer with solar PV, battery storage and an electric vehicle.

The modelling is based on the LUT Energy System model applied to India [18] [19]. The hourly resolution of the model guarantees that for every hour of the year the generated and stored energy covers the total energy demand of the system, which provides precise results. In this case, the net electricity supply which consists of solar PV generation, the battery discharge, discharge from the battery in the EV and withdrawal from the grid meets the net electricity demand that consists of the residential load , charging needs of the EV and charging needs of the battery and the excess solar PV is fed into the grid.

The total annual energy cost of the prosumer is estimated by applying Equation (1), which is to be minimised over a year:

$$Annual\ Energy\ Cost = \sum_i^{technology} (Capex_i \cdot crf_i + Opex_{fix,i} + Opex_{var,i} \cdot E_{throughput,i}) + Cost_{grid} - Income_{feed\text{-}in} \quad (1)$$

Abbreviations stand for: *Capex* – capital expenditure or investment cost for the technology, *crf* – annuity factor, $opex_{fix}$ – fixed operational expenditures, $opex_{var}$ – variable operational expenditures, $E_{throughput}$ – energy handling of component (e.g. discharged energy of the battery), $cost_{grid}$ – cost of electricity supplied by the grid, $income_{feed\text{-}in}$ – income generated from PV electricity fed into the grid [20].

The model was customised for the earlier-mentioned residential prosumer and iterated with solar PV capacity ranging from 1 to 10 kW_p and the corresponding battery capacity ranging from 1 to 15 kWh_{cap}. Further, for a better perspective on the performance of the different components, two scenarios were considered which are, the prosumer without an electric vehicle and the prosumer with an electric vehicle and these are simulated for all 5-year periods from 2015 to 2050, eventually the model estimates the least cost configuration of PV and battery capacity.

Input data for the Indian context is as follows:

A. *Solar generation profile for India*

The input data for PV yield, load profiles are based on 0.45° x 0.45° spatial resolution for a global application, from which the data for India is derived accordingly as shown in Fig. 2 [18]. The annual yield for a solar PV fixed tilted system is 1641 kWh/kW_p [18]. The technical energy storage and battery of the EV storage sizes are set to specific values as shown later.

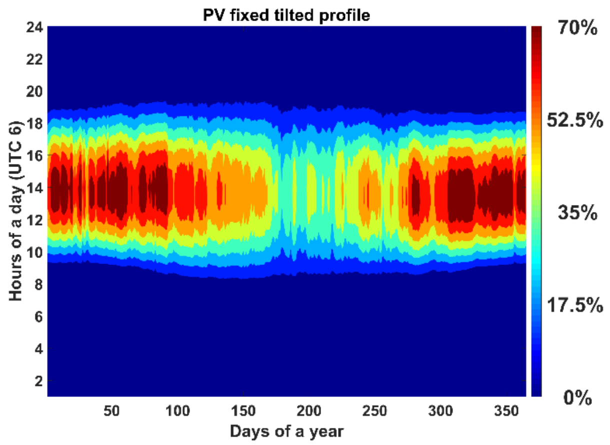

Figure 2. Annual variation of solar profile on hourly basis for India

B. *Household electricity profile*

The household energy demand was derived from the overall electricity load profile of India. The residential share of the overall electricity load is 24% [21][22]. The total number of households in India is around 268.56 million and 88.2% [22] are electrified, with this the hourly load profile of an Indian household is derived and this household electricity demand until 2050 is projected as shown in Fig. 3. The average household electricity consumption rises from 1129 kWh/a in 2015 to 6024 kWh/a in 2050, with a high rate of population growth and GDP expected to grow at 8% per annum till 2030 and 6% beyond that [18].

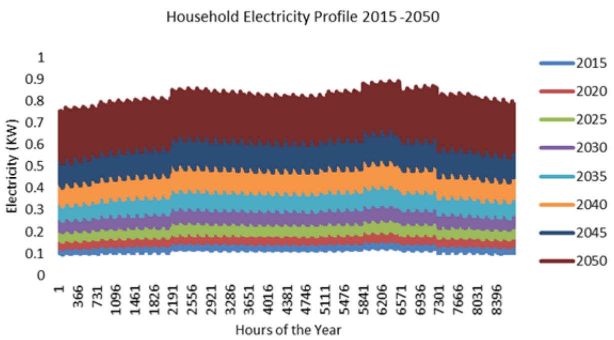

Figure 3. Annual electricity load profile of an Indian household on hourly basis for 2015 - 2050

III. Assumptions

The technical and financial assumptions related to prosumer are as follows:

A. *The storage battery (lithium-ioin)*

The battery is considered to be lithium-ion as indicated earlier, some of the technical assumptions are the same for the battery in the EV as well. The depth of discharge (DoD) is assumed at 95%, efficiency for one way charging is assumed at 96% for both the stationary battery and the battery in the EV and additionally, a safety buffer of 25% is assumed in case of the EV battery for emergency commutes.

B. *The electric vehicle*

The size of the battery for the EV was determined through the consideration of demand per journey of the EV, which is determined as in (2),

$$JD_{EV} = (DD_{annual}/N_{EV}) \cdot C_{EV} \quad (2)$$

Abbreviations stand for: JD_{EV} – Journey Demand (kWh), DD_{annual} = Driving demand per annum (km), N_{EV} = number of journeys, C_{EV} = Consumption rate for EV (kWh/km).

The EV considered in this case is based on average driving pattern of an Indian commuter. It is considered to be used through the week for commuting to work and sparsely used in the weekends. The capacity of the battery in the EV was estimated to be 60 kWh_{cap}, considering an average Indian commuter travels around 10,000 km per annum and conducts around 350 journeys at a consumption rate of 20 kWh/km. This assumption lays well in the design of EVs [23].

C. *Financial assumptions*

The financial assumptions for the different technologies and sources are as follows:

a. Cost of solar PV

The cost of solar PV is as shown in Tab. 1 [18],

TABLE 1: COST ASSUMPTIONS OF ROOFTOP SOLAR PV RESIDENTIAL, 2015-2050

PV Rooftop residential			
Years	**Capex ($€/kW_p$)**	**$Opex_{fix}$ ($€/kW_p a$)**	**Lifetime (years)**
2015	1360	20	30
2020	1169	17.6	30
2025	966	15.7	35
2030	826	14.2	35
2035	725	12.8	35
2040	650	11.7	40
2045	589	10.7	40
2050	537	9.8	40

b. Cost of storage battery

The cost of lithium based batteries used for storage are as shown in Tab. 2 [18],

TABLE 2: COST ASSUMPTIONS OF BATTERY (LITHIUM-ION), 2015-2050

Battery (Lithium)				
Years	**Capex ($€/kWh_{el}$)**	**$Opex_{fix}$ ($€/kWh_{el}a$)**	**$Opex_{var}$ ($€/kWh_{through}$)**	**Lifetime (years)**
2015	600	24	0.0002	15
2020	300	12	0.0002	20
2025	200	8	0.0002	20
2030	150	6	0.0002	20
2035	120	4.8	0.0002	20
2040	100	4	0.0002	20
2045	85	3.4	0.0002	20
2050	75	3	0.0002	20

c. Cost of grid electricity prices

The cost of grid electricity prices in India are as listed in Tab. 3[18],

TABLE 3: GRID ELECTRICITY PRICES IN INDIA, 2015-2050

Grid Electricity Prices India	
Years	**€/kWh**
2015	0.06
2020	0.07
2025	0.09
2030	0.11
2035	0.14
2040	0.17
2045	0.20
2050	0.23

The feed-in tariff is assumed to be 0.02 €/kWh and remain the same until 2050 [18]. In addition, up to 50% of the total solar PV generation is allowed for feed-in remuneration and any excess over 50% is fed into the grid without any incentive. This facilitates the optimal sizing and eliminate oversizing to a certain degree. The cost for utilising the EV for the prosumer cost optimization is not taken into account, as the primary function of the EV is commuting and the capital costs of the EV are considered paid for by the commuter. The commuting pattern has an impact on the usability of the EV as a storage unit, in this case a weekday schedule of EV commuting to work is presumed, wherein the EV is away from 7 am to 6 pm for a total of 11 hours. On weekends, it is assumed to be utilised for recreational journeys, which are to take place in the afternoon and evening between 2 pm and 7 pm. It is decided on a random basis, whether the EV is utilised for recreational journeys on a weekend-day or not. Lifetime of EV batteries seem to benefit from vehicle-to-grid operation [24], as also assumed to happen as part of the PV prosumer optimisation.

IV. RESULTS AND DISCUSSION

The least cost configuration of solar PV and battery for the two scenarios with EV and without EV are shown in Fig. 4 and Fig. 5 respectively.

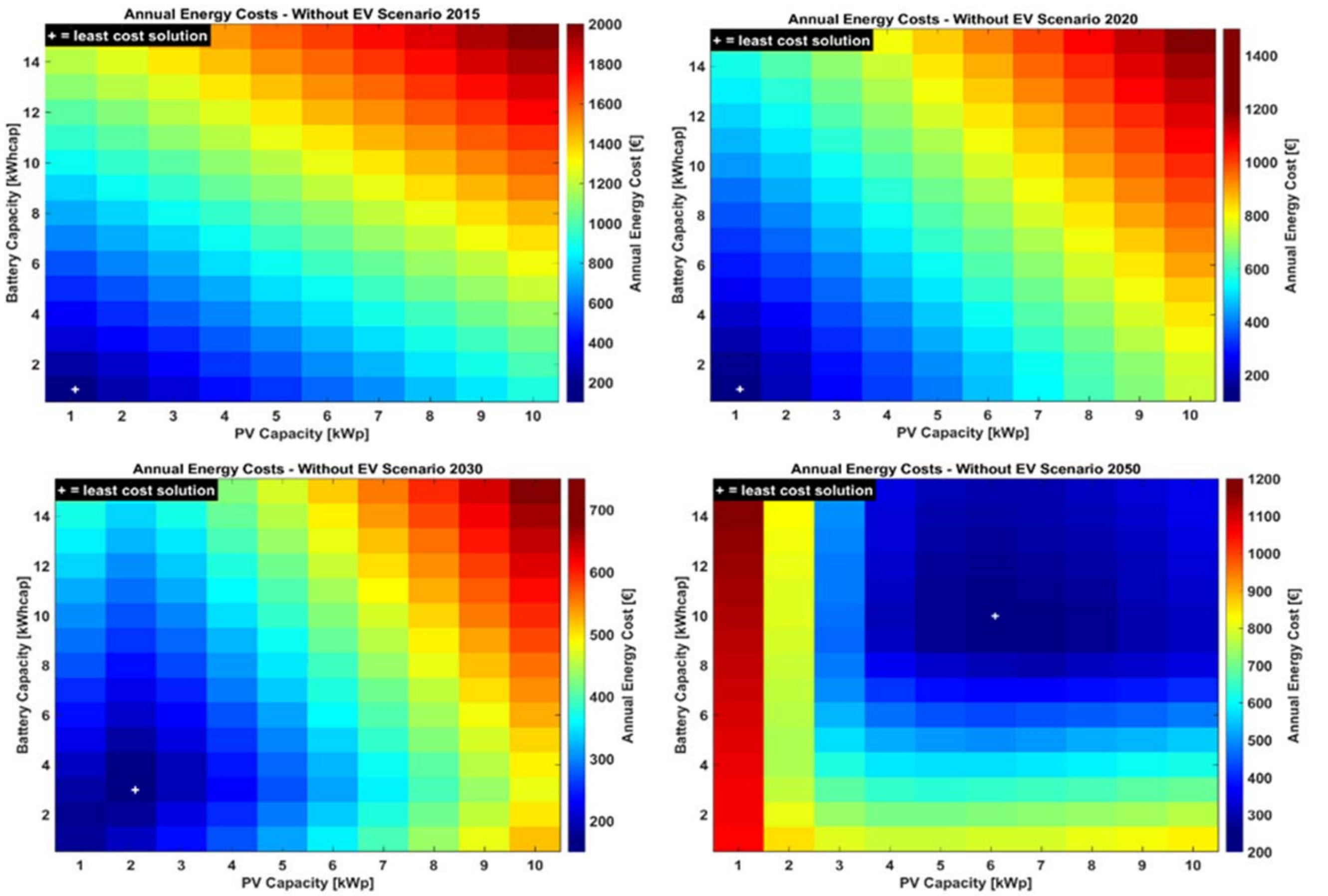

Figure 4: Annual energy cost for ‘No EV’- scenario in 2015 (upper left), 2020 (upper right), 2030 (bottom left) and 2050 (bottom right).

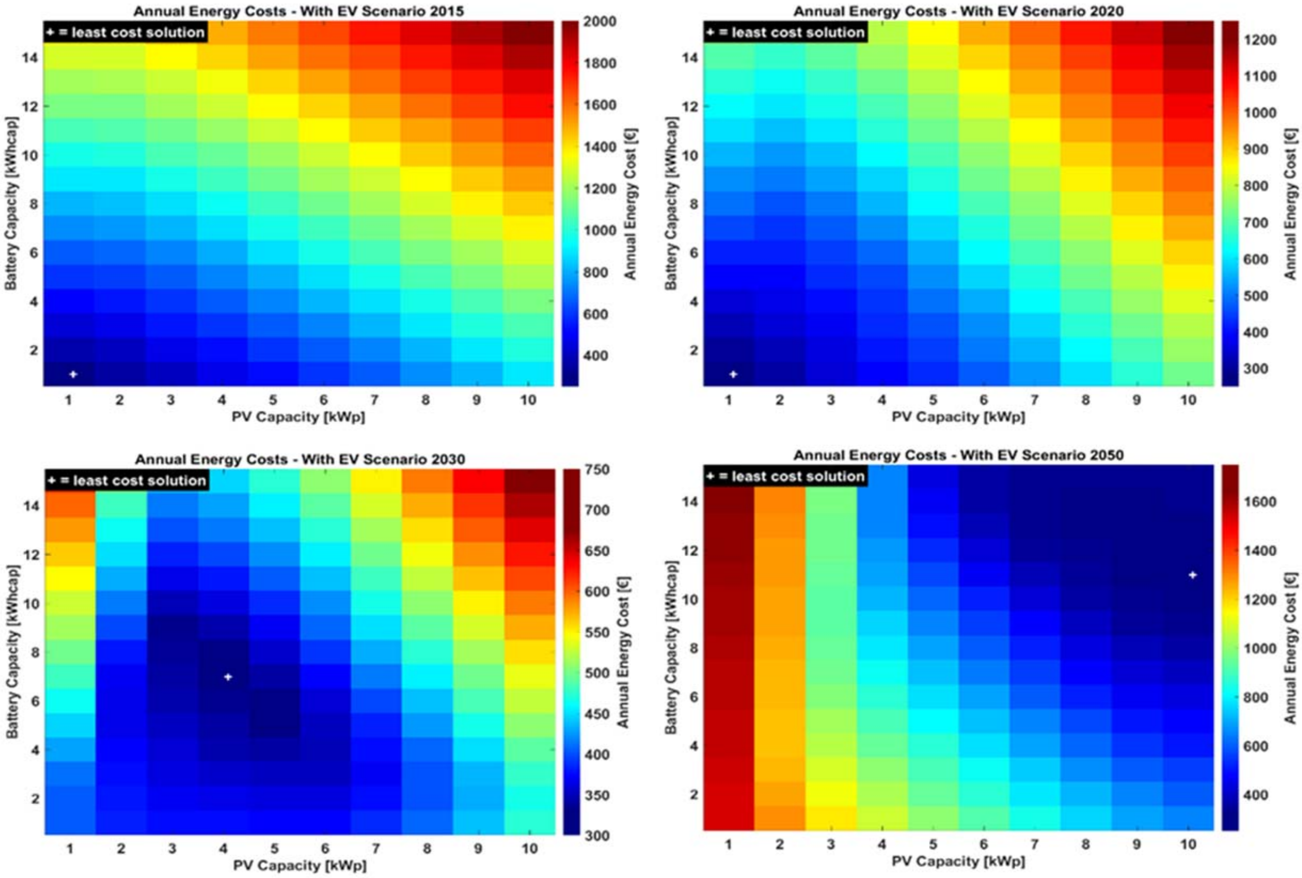

Figure 5: Annual energy cost for 'With EV'- scenario in 2015 (upper left), 2020 (upper right), 2030 (bottom left) and 2050 (bottom right).

Fig. 4 shows the least cost configuration of PV and battery for the years 2015, 2020, 2030 and 2050 for the 'No EV' scenario. They range from 1 kW_p solar PV with 1 kWh_{cap} of battery in 2015 for an annual electricity cost of 177 €/a (12387 INR/a[1]) to 6 kW_p of solar PV with 10 kWh_{cap} of battery in 2050, resulting in an annual electricity cost of 255 €/a (17840 INR/a). Similarly, Fig. 5 shows the least cost configuration of PV and battery for the years 2015, 2020, 2030 and 2050 for 'With EV' scenario. They range from 1 kW_p solar PV with 1 kWh_{cap} of battery in 2015 for an annual electricity cost of 294 €/a (20561 INR/a) to 10 kW_p of solar PV with 11 kWh_{cap} of battery in 2050, resulting in an annual electricity cost of 309 €/a (21655 INR/a).

The results show a tendency for optimal configurations of solar PV and battery to attain the least cost of energy over the year. In both the scenarios, it can be observed that the optimal mix of solar PV and battery capacity remain 1 kW_p and 1 kWh_{cap} respectively until 2025. However, from 2030 onwards solar and battery sizes grow which can be attributed to the decline in costs of solar PV and batteries and the increase in retail electricity prices. This indicates that by 2030 an Indian prosumer household without an EV having an electricity demand of 2313 kWh/a can reduce the annual electricity costs by installing solar PV plus battery storage.

All the least cost options for both the 'No EV' and 'With EV' scenarios in comparison with their corresponding grid electricity costs from 2015 to 2050 are shown in Fig. 6. It can be observed that between 2020 and 2025 the annual electricity costs with PV plus battery is the same as grid electricity costs. However, beyond this PV plus battery options result in substantial savings, as the annual electricity costs remain consistently low in comparison to the annual electricity costs from just grid supply, which keep increasing.

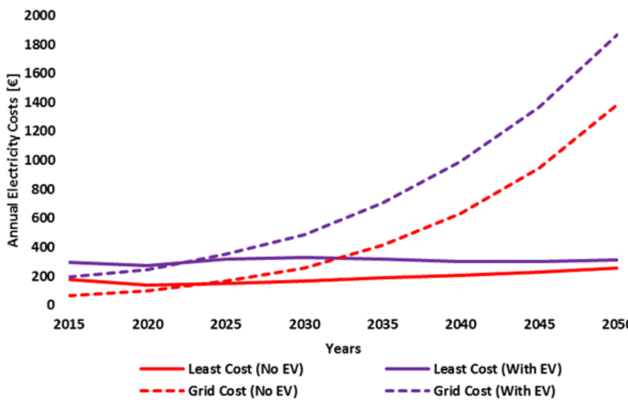

Figure 6: Development of costs for both scenarios, 2015-2050.

In both scenarios, the annual electricity costs are significantly low, which clearly indicates that PV prosumers can benefit greatly in the long term even with low grid electricity prices, as is the case with India in comparison to many countries and a conservative feed-in tariff (0.02 €/kWh), PV plus battery proves to be the most cost effective option. An Indian PV prosumer with no EV can save up to

[1] conversion rate 1€ = 70 INR

1131 €/a (79141 INR/a) and with an EV can save up to 1556 €/a (108905 INR/a) in 2050.

A. Self-Consumption Rate (SCR) and Demand Cover Rate (DCR):

The self-consumption rate is the ratio of the total amount of solar PV electricity consumed by the prosumer to the total amount of solar PV electricity generated by the prosumer. The demand cover rate is the ratio of the total amount of solar PV electricity consumed by the prosumer to the total electricity demand of the prosumer (inclusive of the electricity demand from EV in the case of 'With EV' scenario) [20] [25]. As shown in Fig. 7, the results of the prosumer cost optimisation show an increase in the self-consumption rate initially until 2025 (for both 'No EV' and 'With EV' scenario) and then decrease in the case of 'With EV' scenario and fluctuate with a peak in 2035 (nearly 80%) in the 'No EV' scenario. Whereas, the demand cover rate initially declines (in both 'No EV' and 'With EV' scenario) and then shoots up in 2030 when higher capacities of solar PV and battery are installed. The demand cover rate steadily increases from around 80-90% in 2030 to 98-100% in 2050 for the 'No EV' and 'With EV' scenario respectively.

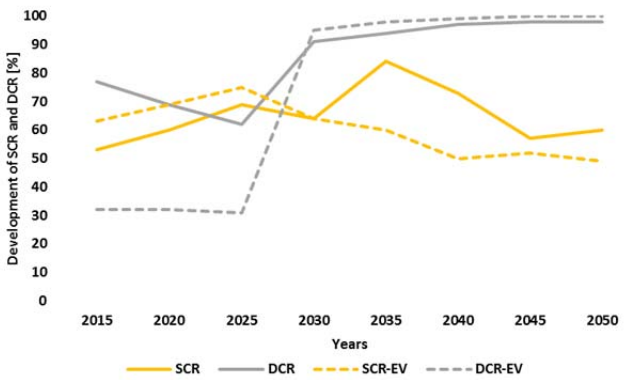

Figure 7: Development of Self-consumption rate (SCR) and Demand-cover rate (DCR) for both scenarios, 2015-2050.

With such high rates of demand coverage, PV prosumers certainly have the potential to decrease the overall supply demand gap. In the case of India, there is a persistent problem of the supply demand gap, which is around 1.6% in 2016 [26]. In the summer months, the power demand is at its peak and with soaring temperatures the demand for cooling results in large additional power requirement. This summer peak demand generally causes power outages in most cities and as showed in Fig. 2, the solar power profile is the highest during these months, which indicates that solar PV prosumers can play a vital role in mitigating this supply demand gap and meeting the summer peaks. In the following section weekly profiles during the summer months is observed more closely for PV prosumers in both 'No EV' and 'With EV' scenarios.

B. The role of PV prosumers in closing the demand supply gap

The excellent solar resource conditions during summer ensure solar PV systems perform efficiently. The Fig. 8 shows the weekly electricity generation and consumption profiles of the Indian PV prosumer with optimal PV and battery capacity in summer for the 'No EV' scenario in 2015, 2030 and 2050 respectively. It can be observed that consumption of grid electricity completely diminishes in 2050. As these are profiles for the least cost configuration of solar PV and battery capacities, they indicate the maximum utilisation of electricity from solar PV generation. Mostly, self-consumption of PV happens during the day time and the excess generation is utilised for charging the battery and the rest is fed into the grid. The battery discharge can be identified to be mostly in the evening hours (which is usually the peak consumption hours of households in India as well as most countries around the world) and meet the residual load of the late night hours. It can be conferred from these profiles that even during summer months; PV prosumers can satisfy almost all their electricity needs with the right capacity of solar PV and battery.

Similarly, Fig. 9 shows the weekly electricity generation and consumption profiles of the Indian PV prosumer with optimal PV and battery capacity in summer for 'With EV' scenario in 2015, 2030 and 2050 respectively. The additional demand of the EV can be noticed readily with the sharp spike in the demand profile. This spike precedes the solar PV profile as the EV is charged in the early morning hours, before the journey (the EV is set to be charged during these times so that it does not add to the evening peak consumption and the EV needs most of its charge for the morning journey). As these are profiles for the least cost configuration, it can be observed from the profile for 2015, which has a low battery storage capacity as PV charges the EV on the weekends. Whereas in 2030 and 2050 it can be observed that a larger portion of the PV is utilised for charging the batteries, which in turn charges the EV during early morning hours after satisfying the evening demand. It can be seen that even with the additional demand from the EV, prosumers can maximise their self-consumption from solar PV generation with the right capacity of battery to complement solar PV generation. In addition, this indicates that the additional electricity demand from EVs will have an impact in the near term, while in the long term the impact is not so high.

C. Effects of large numbers of PV prosumers

As, observed in Fig. 6, turning into a PV prosumer can be a cost effective option. With the rapidly declining costs, and enabling policies being pursued by the Indian government it is quite plausible to foresee a near future with a significant number of solar PV prosumers in the country. Having assumed conservative costs of rooftop solar PV systems for this research show that by 2025, PV plus battery can be cost competitive with grid supply. Whereas, in reality the costs have been declining much faster especially in India, with this trend PV plus battery can be cost competitive much sooner even before 2020 [15] [9]. There are obvious benefits to both consumers and power distribution companies, consumers can turn into prosumers and save energy costs while power distribution companies can buy cheap power from these prosumers and supply to larger commercial and industrial consumers [27]. There are also possible near term impacts on the grid, since a large number of EV's can have an impact on the grid [28]. However, as show in Fig. 9 with the right capacity of PV and battery, this impact of EV can be mitigated.

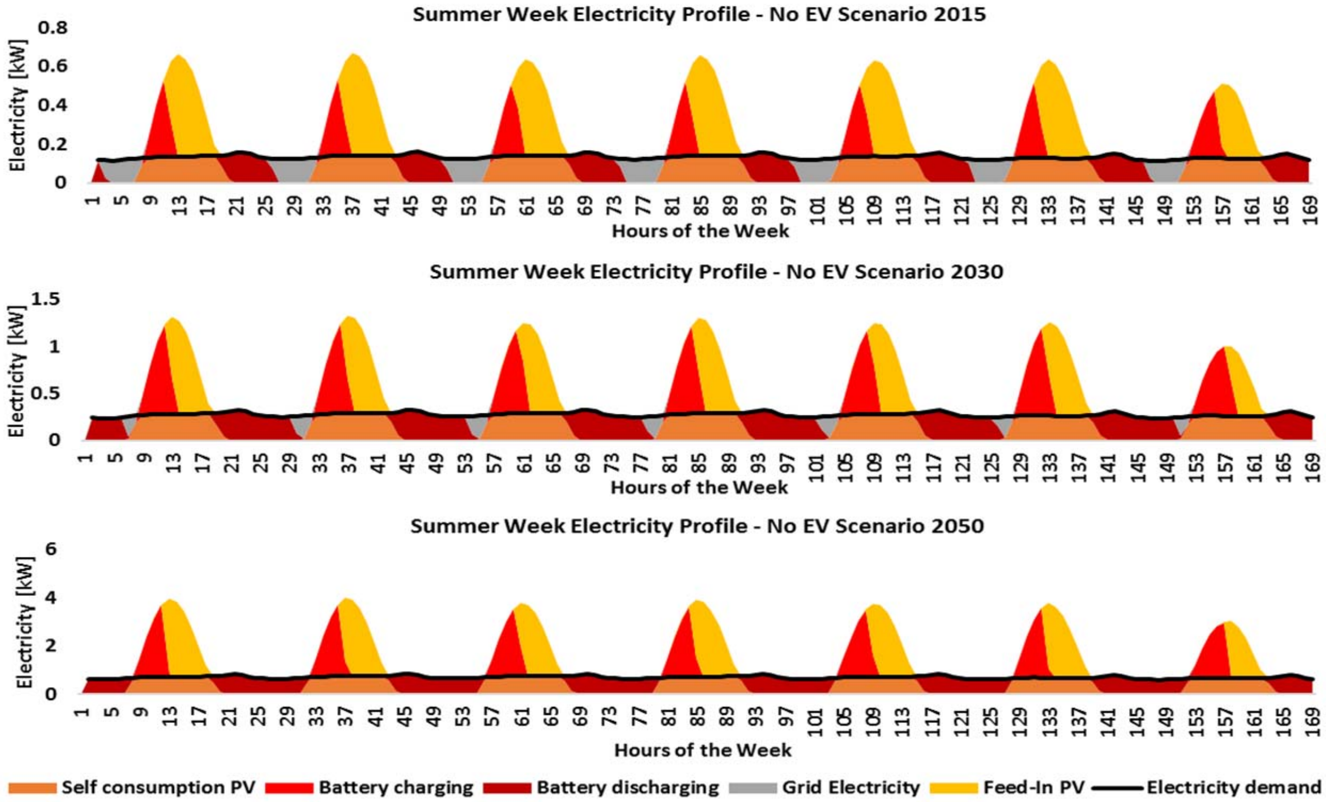

Figure 8: Weekly electricity profiles in summer for the 'No EV' scenario in 2015, 2030 and 2050.

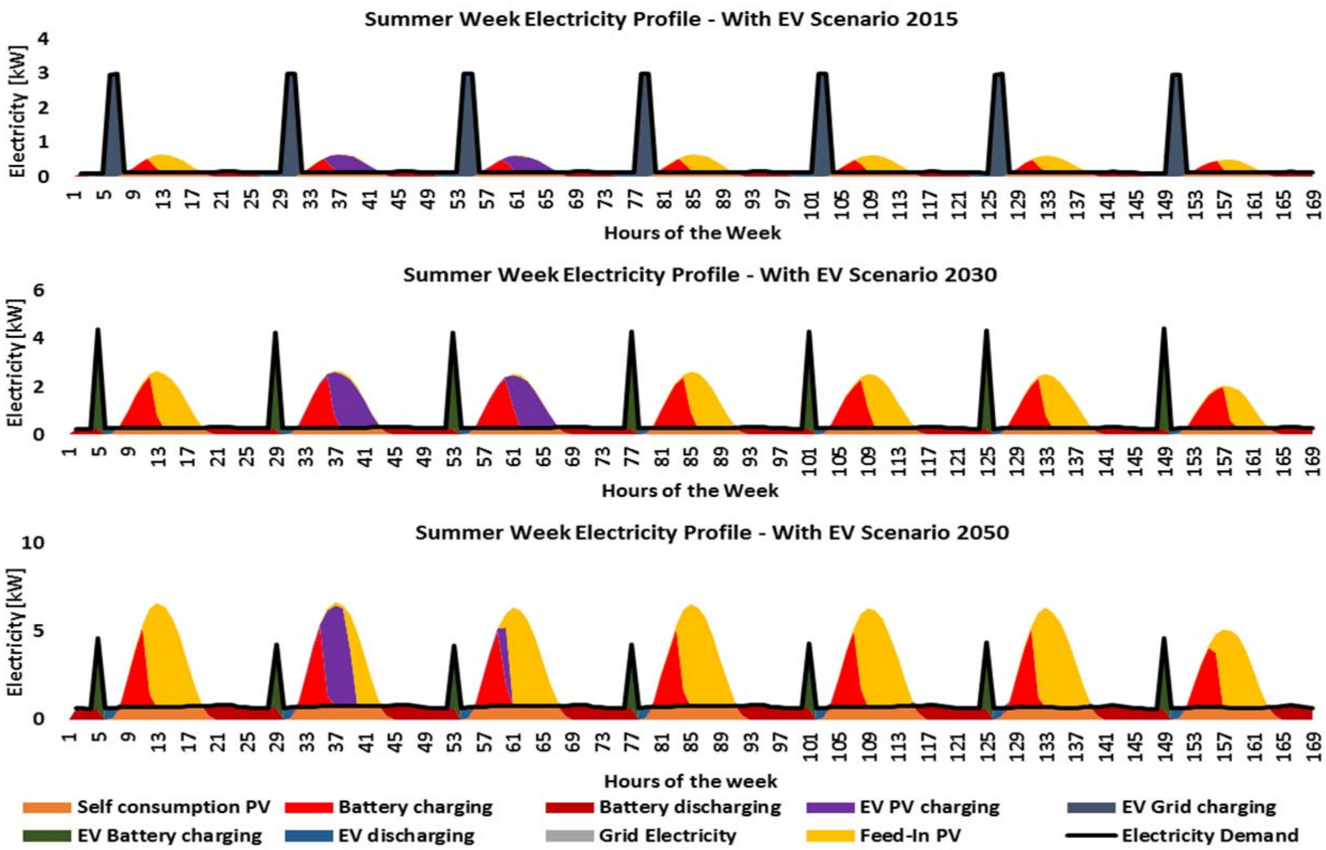

Figure 9: Weekly electricity profiles in summer for the 'With EV' scenario in 2015, 2030 and 2050.

In addition, power distribution companies can plan for the long term, upgrade systems with better management capabilities, and introduce smart application to optimise grid management [29].

Given India's burgeoning electricity demand and the persistent supply demand gap along with the summer shortages and outages, solar PV prosumers will have a crucial role in enabling the country's transition to a fully sustainable energy system.

V. CONCLUSION

As indicated from the results, PV prosumers can benefit greatly by maximising their self-consumption and result in a significant reduction of electricity costs round the year. In addition, with the two scenarios ('No EV' and 'With EV') the utilisation of EV as an energy storage unit for a PV prosumer was observed, which could not only complement the solar PV plus battery combination but also in turn enhance grid integration.

In the longer term, if prices continue to fall at the same rate, solar plus storage will be a genuine alternative to thermal baseload generation sources in the next 3-4 years [13].

The combination of a residential solar PV system and battery storage are highly beneficial for prosumers, particularly with the rapidly declining costs of both PV systems and lithium based batteries [30]. The size of the stationary battery is strongly dependent on the overall electricity demand and the utilisation of EVs and their demand pattern on a daily, as well as yearly basis. Substantial PV prosumer activities may result in challenges for the distribution grid management, but in the same time provide additional flexibility and facilitate better grid integration through smart applications, above all they will be a source for least cost electricity supply for consumers and benefit society as a whole.

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