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Policy Assistance for Adoption of Residential Solar PV in India: A Stakeholder-centric Approach for Welfare Optimization

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Abstract

Background: Domestic solar PV installations in India are yet to become a valuable proposition for both the prosumers and utility because of the deficiencies in the formulation of the policy parameters. This paper presents a comprehensive analysis of the consumer-centric business model for rooftop solar PV installations in India. We explore areas where potential policy interventions may be introduced to improve collective stakeholder benefits and incentivize more domestic consumers to install rooftop solar panels in their premises. We propose a policy framework that seeks optimal Feed-in Tariff (FiT) rates, PV capacities and Average Billing Rates (ABRs) towards maximizing stakeholder benefits. The stakeholders considered are the consumers/prosumers and the utility.

Results: Case studies with three residential prosumers of different demand and generation profiles (extracted from data provided by Indian utilities) are presented. A multi-objective problem is formulated with the FiT, generation capacity (as a function of demand) and ABR as decision variables, exploring the various welfare trade-offs. The pareto-optimal front is identified for prosumer and utility benefits and suitable points with reasonable tradeoff are selected based on sensitivity analysis of the impact of the decision variables on collective welfare.

Conclusions: The paper provides a workflow to fix tariff, FiT and local PV capacities in active residential distribution systems. The suitability of prevailing tariff and FiT rates of three Indian utilities namely, MSEDCL, TATA POWER (Delhi) and TANGEDCO are studied, and their impact on prosumer savings and utility profits is brought out. The paper recommends optimal

installation capacities for prosumers based on their load demand so as to encourage the adoption of roof-top solar without affecting collective benefits. This provides policymakers and prosumers an effective decision-making tool.

Keywords — Feed-in-Tariff, Rooftop Solar PV, Policy, India, Energy

Background

Roof-Top solar PV installations are one of the major approaches proposed to promote distributed generation in India [1]. The market potential for roof-top solar generation is 352GW out of which 124GW is technically feasible. The Ministry of New and Renewable Energy, Government of India has set a target of 40,000MW of roof-top solar generation by 2022. This accounts for 40% of the total solar power generation capacity envisaged by 2022 [2]-[3]. Successful adoption of rooftop PV is vital from the perspective of reducing carbon emissions for which a commitment of 33-35 % reduction by 2030 has been given by India in the Paris Climate Conference in [4]-[5]. It also calls for concerted efforts to educate the consumers on the long term economic [6] and environmental benefits. The successful implementation of this target depends on multiple socio-economic and technical factors such as prevalence of appropriate business models [7] that consider the interests of all stakeholders viz., prosumers, utilities [8], third-party agencies, state, and central governments.

Various implementation approaches and business models with active involvement and facilitation from governments have been reported worldwide. In [9], recommendations for devising policies and tariff structures for adoption of roof-top solar in low irradiance regions are put forward. The relationship between different income levels and solar uptake in Australia is analyzed in [10], thereby bringing out a case for detailed study of socio-economic indicators for policy updates. In [11]-[12], reduction in CO_2 emissions by upgrading all households to comply with energy star standards combined with increased roof-top solar PV installations and optimization for net zero energy homes are addressed. A case-study of a PV agricultural business model is presented in [13] in which greenhouses with rooftop PVs generate revenue from PV generation whereas the greenhouse space is leased out to agricultural ventures thus creating a complete entrepreneurial ecosystem. The lack of penetration of distributed PV among socio-poor sections in California is analyzed using a comprehensive metric *CalEnviroScreen* (CES) in [14]. In [15], the effect of an information campaign in promoting rooftop solar PV installations is quantitatively assessed. The authors report a significant increase in the number of approved applications post the campaign. Agent Based Models are used for

55 simulating solar PV adoption in Great Britain by integrating different socio-economic factors in [16]. The authors
56 provide insights into how different subsidy regimes impact the adoption of the scheme.

57 A stakeholder analysis of the rooftop solar scenario in the Indian states of Jammu and Kashmir and Jharkhand
58 is presented in [17]-[18]. The paper compiles inputs from various stakeholders across different socio-economic and
59 professional categories in the governmental and private sectors. In [19]-[20], comparison of bill saving under net
60 metering [21] to that received under three potential compensation mechanisms is presented. The analysis shows the
61 extent to which net metering can produce significant bill savings across customers. In [22]-[23], new FiT structures
62 that consider electricity price dependence, capacity pricing and energy pricing are proposed to address both individual
63 and societal benefits. The sensitivity of collective benefits to uncertainties in rooftop solar energy output are analyzed
64 using stochastic models in [24]. However, these studies present conclusions based on surveys and feedback
65 questionnaires without analytically modelling the stakeholder benefits. In [25]-[26], the economic viability of the solar
66 PV system is evaluated at different capacities based on net present value (NPV), internal rate of return (IRR) and Pay-
67 Back-Period. The authors show that profitability is highest when net-metering or self-consumption is active but do
68 not provide any recommendations for the optimal settings of PV capacity and FiT. In [27]-[29], the FiT framework,
69 business models and bidding criteria for the support of solar power production in Thailand, USA and India along with
70 the key barriers for adoption are identified with possible remedies such as tax incentives and attractive financing
71 options. In [30], Australia's solar energy policies in terms of FiTs are studied. The study brings out the importance of
72 FiTs in household PV adoption.

73 It is evident from the review of literature worldwide that various mechanisms for promoting and encouraging
74 adoption of distributed roof-top solar PV are being conceived. They include bringing in energy star ratings, new
75 business models, incentivizing low carbon sources, improving ease of establishing renewable powered businesses and
76 agricultural activity, tariff restructuring, subsidies, aggressive campaigning etc. In India, the power distribution sector
77 is still under the process of deregulation with the utility playing a dominant role in financial and technical decision
78 making. The end consumer has no choice in buying and selling (locally generated) power since only a single utility
79 caters to a particular area. Therefore, the present policy scenario does not permit drastic transformation through
80 complete market liberalization. Nevertheless, tuning of prevailing policy parameters like FiT, ABR and PV capacity
81 can definitely make local roof-top solar PV installations an attractive proposition for both prosumers and utilities. In

this paper, the effect of rooftop solar on prosumer savings and utility profit is analyzed for a consumer-centric business model in India. Given the conflicting nature of the objectives namely, prosumer savings and utility profit, a multi-objective problem is formulated with FiT, ABR, Prosumer Demand and PV capacity as decision variables to generate the pareto front. The study explores the net feed-in mechanism by providing room for flexibility in searching the range of FiT values. The sensitivity of the objectives to FiT and PV capacity under the prevailing values of ABR and ACOS is analyzed to extract pareto points providing reasonable trade-offs for the stakeholders. Three Indian utilities, MSSEDCL, TATA POWER, Delhi and TANGEDCO are considered for the study based on availability of data. Policy recommendations are provided for tuning the FiT, ABR and PV capacity for the aforementioned utilities.

The paper is organized as follows: Section 2 describes the methodology adopted for modeling the stakeholder benefits and their pareto optimization. Section 3 presents the results of sensitivity analysis and multi-objective optimization along with the policy recommendations. Section 4 lists out policy suggestions with concluding remarks and outlines future directions.

Methodology

The prevailing business models for roof-top solar implementation in India are: 1) Consumer centric, 2) Renewable Energy Service Company (RESCO) based, and 3) Utility facilitated. In the consumer centric model, the consumer bears the capital and operational expenditure for the rooftop installation and has complete ownership of the system. In the RESCO based model, the RESCO sets-up the PV system on the rooftop of the customer and signs a PPA (Power Purchase Agreement) with the consumer. The investment is recovered through the solar energy tariff. In the utility facilitated model, the installation is owned and managed by the utility with the prosumer compensated either through bill discounts or other incentives.

In this paper, two types of residential premises are considered. The ones with installed rooftop solar PV panels are called *prosumers*. Those without local self-generation are referred to as *consumers*. The case study is confined to residential prosumers/consumers in the low voltage distribution system. The prosumers are classified into three categories based on the range of installed PV capacities. In India, maximum permissible PV capacities are limited to 8-10 kW depending on the utility. The categories are 1-3 kW, 3-5 kW and 5-8 kW. The classification is necessitated because a single policy recommendation for the entire range of 1-8 kW is impractical due to the large difference in

capital investment cost. The stakeholders are the prosumers and the utility. The benefit of the prosumer is modelled in terms of the savings obtained on adoption of rooftop solar after considering the EMI outgo towards the installation cost and income from sale of locally generated rooftop solar energy. The benefit of the utility is the profit earned from the sale of energy at ABR after considering the cost of procurement of energy. The formulation of the prosumer savings and utility profit equations is explained in detail in Section 2.1. The trade-offs involved in ensuring reasonable benefits for the stakeholders are explored by tuning the key decision variables related to installed capacity, load demand and feed-in-tariff rates.

Modelling the economics of stakeholders

The consumer-centric business model shown in Fig.1 is analysed in this paper. In this model, the potential prosumer has to bear the complete capital and operational expenditure of the rooftop solar PV installation. The consumer contacts an EPC firm to set up the installation at his/her premises. Based on the metering regulation, the financial and energy settlements are done through net or gross-metering arrangements [31]. The prosumer consumes the locally generated solar energy, and the surplus energy is exported to the utility at Feed-in-Tariff. In case, the local generation is not sufficient, the prosumer imports energy from the utility at retail tariff rate.

Fig. 1. Consumer-centric business model

The equations describing the components of the utility profit and prosumer savings are given in Table 1. Revenue and expense of the utility are modelled by equations (1) and (2) respectively. The terms of equations (1) are described in rows 1-3 of Table 1. The terms of equation (2) are specified in Rows 5 and 6 respectively. The term k is defined as shown in equation (3). Its value depends on whether the prosumer has an excess or deficit of energy. The profit of utility is shown in equation (4). The monthly electricity bill that the prosumer would have incurred in

the absence of rooftop solar PV installation is given by equation (5), whose individual terms are defined in rows 10 and 11 of Table 1. Equation (6) computes the prosumer's electricity bill considering local generation from solar PV. Its terms are explained in rows 13, 14, 15 and 17 of Table 1. EMI is calculated using equation (7) where p is the total installation cost, r is the rate of interest and n is the payback period. The savings of prosumers is modelled by equation (8).

TABLE. 1. DETAILS OF PROSUMER SAVINGS AND UTILITY PROFIT EQUATIONS

Row No.	Term	Description	
1	$(E_{dc} \times abr)$	Earnings from the sale of energy at ABR to non-rooftop solar consumers	
2	$(E_{gp} - E_{dp}) \times (k - 1) \times abr$	Earnings from the sale of deficit energy at ABR from prosumer	
3	$FC \times (n_p + n_c)$	Fixed monthly charge from the prosumers and consumers	
4	$Rev_{uti} = (E_{dc} \times abr) + \{(E_{gp} - E_{dp}) \times (k - 1) \times abr\} + FC \times (n_p + n_c)$		(1)
5	$k \times (E_{gp} - E_{dp}) \times FiT$	Purchase of energy from prosumers at FiT	
6	$\{E_{dc} - (E_{gp} - E_{dp})\} \times acos$	Purchase of remaining energy to meet the demand of the system from the upstream grid at ACoS	
7	$Exp_{uti} = k \times (E_{gp} - E_{dp}) \times FiT + \{E_{dc} - (E_{gp} - E_{dp})\} \times acos$		(2)
8	$k = \begin{cases} 1 & (E_{gp} - E_{dp}) > 0 \\ 0 & (E_{gp} - E_{dp}) < 0 \end{cases}$		(3)
9	$Profit_{uti} = [\{E_{dc} \times (abr - acos)\} - \{(E_{gp} - E_{dp}) \times (abr \times (1 - k) - acos)\}] + [FC \times (n_p + n_c)] - [k \times (E_{gp} - E_{dp}) \times FiT]$		(4)
10	$E_{dp} \times abr$	Cost of purchase of energy at ABR by prosumer	
11	$FC \times n_p$	Monthly fixed charge by prosumer	
12	$Bill_{without solar} = E_{dp} \times abr + FC \times n_p$		(5)
13	$(1 - k) \times (E_{dp} - E_{gp}) \times abr$	The cost of purchase of deficit energy at ABR	
14	$(E_{dp} - E_{gp}) \times FiT \times k$	The revenue from the sale of surplus energy at FiT	
15	$FC \times n_p$	Monthly fixed charge by prosumer	
16	$Bill_{with solar} = (1 - k) \times (E_{dp} - E_{gp}) \times abr + (E_{dp} - E_{gp}) \times FiT \times k + FC \times n_p + EMI$		(6)
17	$EMI = p \times r \times \frac{(1+r)^n}{(1+r)^n - 1}$		(7)

18	$Saving_{pro} = Bill_{without\ solar} - Bill_{with\ solar}$ $= [E_{dp} \times abr + FC \times n_p] - \{ (E_{dp} - E_{gp}) \times [(1 - k) \times abr + FiT \times k] + FC \times n_p + EMI \}$	(8)
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From equations (4) and (8), it is evident that the utility profit and prosumer savings depend on the following parameters: a) Feed-in Tariff (FiT) b) ABR c) PV panel size and d) Monthly Energy Demand of prosumer (E_{dp}). Among these parameters, FiT and ABR are fixed by the utility whereas PV capacity and E_{dp} are decided by the prosumers. The ABR values are derived from the category-wise revenue numbers of the utility [32]. ACoS is defined as the ratio of the total cost for providing power supply to the end consumer to total electricity input/purchased for the total number of consumers [33].

Determination of pareto-optimal solution

The objective functions are utility profit and prosumer savings given respectively in equations (4) and (8). They are found to be conflicting in nature thereby necessitating a multi-objective optimization approach to explore and identify reasonable trade-offs from the pareto front shown in Figure. 3.

Fig. 2. Decision making flowchart for framing policies for residential rooftop PV installations

The methodology to assist policy makers in identifying suitable ranges for the parameters ABR, FiT, PV capacity and Energy Demand is depicted in Figure 2. At the outset, the number of consumers and prosumers is defined. This is followed by development of profit and savings equations for the selected business model (consumer-centric in this case). Then the constraints to the multi-objective algorithm are defined in terms of the maximum and minimum limits of the decision variables. The value of k is set to 1 if the energy generated by solar is greater than the energy demand of the prosumer and is set to 0 otherwise. The prevailing ACoS and fixed charge of utility along with the EMI and set k values are used for profit and saving calculations using equations (4) and (8). Finally, the pareto front as shown in Fig.3 is extracted using non-dominated sorting algorithm. The minimum expected utility profit and prosumer savings are first laid down by the policy makers to ensure that rooftop PV installations are an attractive proposition for the prosumers. Also, the scheme must be designed in such a way that it is viable to the utility. Keeping these in mind, a subset of points in the pareto front is chosen, thus yielding the rationalized range of ABR, FiT, rooftop PV capacity and load demand. This serves as a guideline for framing policy recommendations.

Fig. 3. Pareto-front for utility profit versus prosumer savings

Results and Discussion

The proposed methodology is applied to evaluate a distribution test system having two prosumers and three consumers. The search space of the multi-objective optimization algorithm is defined by the constraints of the decision variables FiT, PV size, and E_{dp} as shown in Table. 2 [34]-[36].

Three Indian utilities namely MSEDCL, TANGEDCO, and TATA power are considered for the study with their prevailing values of ABR and ACoS. Also, the analysis is repeated for ABR values ranging from 100 to 120% of ACOS

170

TABLE. 2. RANGES OF DECISION VARIABLES AND CONSTRAINTS

Parameter	MSEDCL	TATA	TANGEDCO
ABR (Rs/kWh)	7.32	4.96	4.32
ACoS (Rs/kWh)	7.61	7.31	5.85
FiT (Rs/kWh)	1 - 4.2		
E_{dp} (kWh)	50% to 150 % of E_{gp} (50% of E_{gp} for sensitivity analysis)		
PV capacity (kW)	1 - 8		

171 **Case 1: MSEDCL (Maharashtra)**

172 The pareto-optimal points for different PV panel sizes are shown in Fig.4 in which absolute values of
 173 prosumer saving are plotted against the utility profit. Fig.4 suggests that the best trade-offs for absolute values of
 174 utility profit and prosumer savings are in the range of 5-8 kW PV capacities. However, 1-3 kW PV capacities yield
 175 reasonable trade-offs in terms of percentages (see Table 6).

176

177 Fig. 4. Pareto optimal points for different PV ranges

178 Table. 3 and Table. 4 present the sensitivity analysis of utility profit and prosumer savings with respect to variations
 179 in FiT and PV capacities respectively for 1-3 kW and 3-5 kW. The sensitivity analysis is carried out for E_{dp} values
 180 ranging from 50% to 150% of E_{gp} in steps of 25%. A representative case where E_{dp} is 50% of E_{gp} is depicted in
 181 Tables 3, 4 and 5. From Table 3, it is evident that prosumer savings increase with installed capacity only for FiTs
 182 above 2.2 Rs/kWh when local prosumer generation exceeds prosumer demand ($E_{gp} \geq E_{dp}$). For $FiT \geq 2.2$ Rs/kWh,
 183 the utility profit and prosumer savings range from 11 % to 28 % and 51 % to 66 % respectively. This is observed at
 184 E_{dp} values ranging from 55 % to 95 % of E_{gp} . For the lowest range of 1 to 3 kW PV capacities, the pareto front yields

panel sizes of 2.7-3 kW with the best trade-off observed at 3 kW. Thus, it follows that roof-top PV installations in the 1-3 kW range offer a win-win situation only at the maximum panel size of 3 kW for $FiT \geq 2.2$ Rs/kWh.

TABLE. 3. SENSITIVITY OF PROSUMER SAVINGS AND UTILITY PROFIT TO PV SIZE (1-3 KW) AND FiT

Prosumer Saving (%)										
FiT (Rs/kWh)		1	1.4	1.8	2.2	2.6	3	3.4	3.8	4.2
PV size (kW)	2.7	49.4%	54.4%	59.5%	64.5%	69.6%	74.7%	79.7%	84.8%	89.8%
	2.8	48.3%	53.7%	59.1%	64.5%	70.0%	75.4%	80.8%	86.3%	91.7%
	2.9	47.1%	52.9%	58.7%	64.5%	70.3%	76.2%	82.0%	87.8%	93.6%
	3	46.0%	52.2%	58.4%	64.5%	70.7%	76.9%	83.1%	89.3%	95.4%
Utility Profit (%)										
PV size (kW)	2.7	35.4%	33.5%	31.6%	29.6%	27.7%	25.8%	23.8%	21.9%	20.0%
	2.8	37.8%	35.7%	33.7%	31.6%	29.5%	27.4%	25.3%	23.3%	21.2%
	2.9	40.2%	38.0%	35.7%	33.5%	31.3%	29.1%	26.9%	24.6%	22.4%
	3	42.5%	40.2%	37.8%	35.4%	33.1%	30.7%	28.4%	26.0%	23.6%

TABLE. 4. SENSITIVITY OF PROSUMER SAVINGS AND UTILITY PROFIT TO PV SIZE (3-5 KW) AND FiT

Prosumer Saving (%)										
FiT (Rs/kWh)		1	1.4	1.8	2.2	2.6	3	3.4	3.8	4.2
PV size (kW)	4.7	31.9%	37.1%	42.3%	47.6%	52.8%	58.0%	63.2%	68.4%	73.7%
	4.8	30.8%	36.2%	41.7%	47.1%	52.6%	58.0%	63.5%	68.9%	74.4%
	4.9	29.7%	35.4%	41.1%	46.7%	52.4%	58.1%	63.7%	69.4%	75.1%
	5	28.7%	34.5%	40.4%	46.3%	52.2%	58.1%	64.0%	69.9%	75.8%
Utility Profit (%)										
PV size (kW)	4.7	35.6%	33.5%	31.4%	29.3%	27.1%	25.0%	22.9%	20.8%	18.7%
	4.8	37.1%	34.9%	32.7%	30.5%	28.3%	26.1%	23.9%	21.7%	19.5%
	4.9	38.6%	36.3%	34.0%	31.7%	29.4%	27.1%	24.8%	22.5%	20.2%
	5	40.1%	37.7%	35.3%	32.9%	30.5%	28.1%	25.8%	23.4%	21.0%

TABLE. 5. SENSITIVITY OF PROSUMER SAVINGS AND UTILITY PROFIT TO PV SIZE (5-8 KW) AND FiT

Prosumer Saving (%)										
FiT (Rs/kWh)		1	1.4	1.8	2.2	2.6	3	3.4	3.8	4.2
PV size (kW)	7.7	32.5%	37.8%	43.1%	48.4%	53.7%	59.0%	64.4%	69.7%	75.0%
	7.8	31.8%	37.2%	42.7%	48.2%	53.6%	59.1%	64.5%	70.0%	75.4%
	7.9	31.1%	36.7%	42.3%	47.9%	53.5%	59.1%	64.7%	70.3%	75.9%
	8	30.4%	36.2%	41.9%	47.6%	53.4%	59.1%	64.8%	70.6%	76.3%
Utility Profit (%)										
PV size (kW)	7.7	39.4%	37.0%	34.6%	32.2%	29.7%	27.3%	24.9%	22.4%	20.0%
	7.8	40.5%	38.0%	35.5%	33.0%	30.5%	28.0%	25.5%	23.0%	20.5%
	7.9	41.5%	39.0%	36.4%	33.9%	31.3%	28.7%	26.2%	23.6%	21.1%
	8	42.6%	40.0%	37.3%	34.7%	32.1%	29.5%	26.8%	24.2%	21.6%

Higher the PV size, more will be the export so that the utility is able to procure energy at FiT. Since the FiT is lower than ACoS, this results in a reduction in cost of procurement. The energy procured from the prosumers is sold at ABR which is higher than the FiT, thereby yielding a better profit for the utility. For 1-3 kW PV capacities, the EMI outgo is compensated by the receipts from the sale of energy only at FiTs greater than or equal to 2.2 Rs/kWh. This results in an increasing trend in utility profit with increasing PV sizes. For capacities in the ranges 3-5 kW and 5-8 kW, the EMI is compensated only at FiTs of 3 Rs/kWh and above because of the higher EMI in these ranges (see Tables 4 and 5). EMI variation is found to be non-linear and non-uniform for variations in PV capacities. At lower PV sizes (where $E_{dp} \geq E_{gp}$), utility profit does not change with increasing FiT as there is no export. The profit is contributed only by the fixed charges plus the revenue from the consumers billed at ABR. In a low FiT regime, the prosumer savings peak at a PV capacity where the generation balances the demand. Therefore, it is recommended that a PV capacity that results in balancing demand and generation be chosen if the FiT's are low, to maximize prosumer savings.

Table 6 summarizes the optimal ranges of FiTs, E_{dp} , PV capacities and the corresponding prosumers savings and utility profits. It is found that for existing ABR & ACoS values, the E_{dp} ranges from 50% to 90% of the local solar generation. The optimal FiT ranges should be from Rs 2.2 to 4.1 per kWh for lower PV range 1-3 kW and from Rs 3 to 4.1 per kWh for the higher PV range of 3-8 kW. It is observed that a profit of at least 10% is earned by the utility only at maximum PV capacities of 3 kW, 5 kW and 8 kW respectively for the ranges under consideration. Compared to prosumer savings, utility profits are found to be relatively low in the range 10-28 % across PV capacities because of the prevailing ABR being less than ACoS for MSEDCL.

TABLE. 6. ANALYSIS FOR DIFFERENT PV CAPACITY RANGES MSEDCL

PV panel size (kW)	FiT range (Rs/kWh)	E_{dp} range (%)	Optimum PV Capacity (kW)	Prosumer Saving (%)	Utility Profit (%)
1-3	2.2 - 4.1	55 - 95	3	51 - 66	11 - 28
3-5	3 - 4.1	60 - 90	5	58 - 66	10 - 24
5-8	3 - 4.1	60 - 90	8	59 - 68	10 - 24

In Table 7, the analysis is repeated with a higher ABR set to 120 % of the prevailing ACoS. As a result, the utility profit significantly improves to 20-48%. Further, the benefits are extended to prosumers in the entire E_{dp} range considered for the study.

TABLE. 7. ANALYSIS FOR DIFFERENT PV CAPACITY RANGES WITH PROPOSED ABR

PV panel size (kW)	FiT range (Rs/kWh)	E_{dp} range (%)	Optimum PV Capacity (kW)	Prosumer Saving (%)	Utility Profit (%)
1-3	1-4.2	60-130	3	51-70	25-40
3-5	1-4.2	60-150	5	44-70	21-45
5-8	1-4.2	55-135	8	50-75	20-48

Case 2: TATA Power (Delhi)

The pareto-fronts for different PV capacities are shown in Fig.5. A trend similar to that in Case 1 is seen where the best trade-offs in terms of percentages are observed for PV capacities in the range 1-3 kW. On the other hand, in absolute terms, a win-win situation occurs at PV capacities in the range 5-8 kW. From Table 8, it is found that for the prevailing ABR & ACoS values, the optimal E_{dp} ranges from 50% to 60% of E_{gp} . Further, the optimal FiT ranges from Rs 1 to 1.3 per kWh for lowest PV capacities 1-3 kW and from Rs 1 to 1.5 per kWh for higher PV capacities of 3-8 kW. From Table 9, it is found that if the value of ABR is set to 120% of ACoS, then the profit is significantly improved from 8-13 % to 20-48 % across PV capacities. The rise in profits is due to the higher revenue for the utility on account of the increase in ABR. The prevailing ABR is 4.96 Rs/kWh and ACoS is 7.31 Rs/kWh for TATA power. In this case, the utility profits and prosumer savings are less compared to MSEDCL, as the prevailing ABR is much less than ACoS for TATA Power.

Fig. 5. Pareto optimal points for different PV ranges

TABLE. 8. ANALYSIS FOR DIFFERENT PV CAPACITY RANGES TATA POWER

PV panel size (kW)	FiT range (Rs/kWh)	E_{dp} range (%)	Optimum PV Capacity (kW)	Prosumer Saving (%)	Utility Profit (%)
1-3	1 - 1.3	60	3	13 - 17	11 - 13

3-5	1 - 1.2	50	5	2 - 6	11 - 13
5-8	1.2 - 1.5	60	8	16 - 20	8 - 9

TABLE. 9. ANALYSIS FOR DIFFERENT PV CAPACITY RANGES WITH PROPOSED ABR

PV panel size (kW)	FiT range (Rs/kWh)	E_{dp} range (%)	Optimum PV Capacity (kW)	Prosumer Saving (%)	Utility Profit (%)
1-3	1.1-4	55-130	3	48-69	25-48
3-5	1.3-4.1	50-145	5	45-72	22-43
5-8	1-4.2	55-135	8	48-68	20-48

Case 3: TANGEDCO (Tamil Nadu)

The pareto optimal points for different PV ranges are shown in Fig.6. From Table 10, it is found that for prevailing ABR & ACoS values, the optimal E_{dp} ranges from 50-60% of E_{gp} & optimal FiT ranges from Rs 1-1.3 per kWh respectively for lower PV range 1-3 kW and above 1.8 Rs/kWh for higher PV range from 3 to 8 kW. From Table 11, it is observed that if the value of ABR is set to 120% of ACoS, then the profit gets significantly increased to 19-46% from 8-15 % across PV capacities. This can be attributed to the low prevailing ABR values as is the case with TATA power (refer Case 2).

Fig. 6. Pareto optimal points for different PV ranges

TABLE. 10. ANALYSIS FOR DIFFERENT PV CAPACITY RANGES TANGEDCO

PV panel size (kW)	FiT range (Rs/kWh)	E_{dp} range (%)	Optimum PV Capacity (kW)	Prosumer Saving (%)	Utility Profit (%)
1-3	1-1.3	60	3	2-6	12-15
3-5	1.8	50	5	5	8

5-8	1.2 - 1.5	60	8	5-10	10-12
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TABLE. 11. ANALYSIS FOR DIFFERENT PV CAPACITY RANGES WITH PROPOSED ABR

PV panel size (kW)	FiT range (Rs/kWh)	E_{dp} range (%)	Optimum PV Capacity (kW)	Prosumer Saving (%)	Utility Profit (%)
1-3	1.6-4.2	50-130	3	44-62	22-38
3-5	1-4.1	55-145	5	39-64	20-44
5-8	1-4.1	50-140	8	38-63	19-46

Conclusion and Policy Implications

- A cost-benefit analysis of the consumer-centric business model for domestic rooftop solar PV installations in India is carried out to identify optimal policy parameters yielding reasonable trade-offs in stakeholder benefits. To this end, a multi-objective optimization problem is formulated, with utility profit and prosumer savings as objectives.
- The results indicate that for prevailing ABR and ACoS values, the local rooftop PV capacity should be chosen such that there is net export of power by the prosumer. This is due to lower prevailing ABR compared to ACoS. On the other hand, when prosumer demand exceeds generation, the utility incurs losses due to lower ABR.
- It is observed that the maximum PV panel capacity yields better trade-offs for all the three ranges considered. For lower capacity installations, both prosumer savings and utility profits are affected with the prevailing values of FiT and ACoS.
- When ABR is set to 120% of ACoS, the pareto front yields a wider range of FiT and E_{dp} with reasonable trade-offs. This is because the major share in prosumer savings is from solar energy self-consumption. At the same time, the low FiT values yield better utility profits because of higher ABR. Even PV installations of smaller capacities turn out to be profitable to the utility and beneficial to the prosumer at higher ABR values. Hence, tariff rationalization is recommended to make large-scale adoption of rooftop PV by domestic consumers a win-win proposition. However, drastic changes in residential tariff would face socio-political challenges
- In case of MSEDCL, for a guaranteed minimum utility profit of 10%, the average energy demand of prosumer should be around 70% of E_{gp} . For TATA power, for the same targeted minimum utility profit of 10%, the

average energy demand of prosumer turns out to be around 56% of E_{gp} . In case of TANGEDCO, the minimum profit is guaranteed at an average prosumer demand of 56% of E_{gp} .

- Across the utilities, it is seen that with the prevailing ABR and ACoS values, if the prosumers consume 50 to 60% of local solar PV generation, both the utility and prosumer are benefited.
- For TATA POWER and TANGEDCO, the prevailing ABR values are less than ACoS because of which they incur losses. Hence, rooftop solar is an economic proposition for the utility as it helps them to procure energy at a lower FiT. It is sold to non-rooftop consumers at ABR thus yielding a reasonable profit. On the other hand, the prosumer savings are less compared to MSEDCL because of the lower ABR values.
- The recommendations of the study are made with a minimum category-wise (residential consumers here) guaranteed profit for the utility. However, Indian utilities resort to cross-subsidizing low-income groups by charging higher tariffs for industrial and commercial consumers and thereby offsetting the losses incurred for subsidized power. Other consumer categories will be included in the study as part of future work.
- In this work only the consumer-centric business model has been explored. The other business models involving third party agencies (RESCO based models) will be taken up as future work.

Acronyms

ABR	Average Billing Rate
ACoS	Average Cost of Supply
EB	Electricity Board
EPC	Engineering, Procurement and Construction
<i>FiT</i>	Feed-in-Tariff
MSEDCL	Maharashtra State Electricity Distribution Corporation Limited
PPA	Power Purchase Agreement
TANGEDCO	Tamilnadu Generation and Distribution Corporation Limited

Nomenclature

<i>abr</i>	Average billing rate (Rs/kWh)
<i>acos</i>	Average cost of supply (Rs/kWh)

$Bill_{with\ solar}$	Monthly bill paid by prosumer to utility with solar (Rs)
$Bill_{without\ solar}$	Monthly bill paid by prosumer to utility without solar (Rs)
E_D	Total energy demand (kWh)
E_{gp}	Total energy generation by prosumer (kWh)
E_{dp}	Energy demand of prosumer (kWh)
E_{dc}	Energy demand of consumer (kWh)
Exp_{uti}	Expense of utility (Rs)
FC	Fixed charge (Rs)
k	Binary constant taking value of 1 or 0
n_c	Number of consumers
n_p	Number of prosumers
n	Payback period (months)
p	Total installation cost of PV panel (Rs)
r	Monthly rate of interest (%)
Rev_{uti}	Revenue of utility (Rs)
$Saving_{pro}$	Saving of prosumer (Rs)

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286 **Declarations**

287 **Ethics approval and consent to participate**

288 Not Applicable

289 **Consent for publication**

290 Not Applicable

291 **Availability of data and materials**

292 All data generated or analysed during this study are included in this published article.

293 **Competing interests**

294 The authors declare that they have no competing interests

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Authors' contributions

VM: Conceptualization, Methodology, Writing – original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. HRDS: Conceptualization, Methodology, Writing – original draft, Writing - review & editing, Supervision, Project administration. GP: Data curation, Software, Writing - original draft, Formal analysis. JM: Data curation, Software, Writing - original draft, Formal analysis. RCU: Supervision, Investigation, Project administration, NK: Conceptualization, Methodology, Supervision. KT: Supervision, Project administration Funding acquisition. SB: Supervision, Project administration Funding acquisition. All authors read and approved the final manuscript.

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