3 RESULTS AND DISCUSSION

3.1 Annual savings in IPV

In net metering with SDT/UDT, only REC 5 had a surplus in PV energy in September (fig14). Most consumers had surplus PV energy between October-April. The accumulated energy credits were carried over to the next month to compensate for power bills. These credits were used mainly in the months of May-August when energy demand overtook PV energy production (fig 15). At the end of the 12-month period, REC2 had the largest energy credit of 595 units. REC3 had zero credits in July and August. This was due to the undersized PV system of REC3. As outlined earlier, REC3 is restricted to having a PV system of 3.96 kWp due to regulations. Domestic consumers in Delhi having energy units purchased from grid up to 200 kWh are fully exempted to pay any charges to DISCOM (including fixed charges). After adjusting energy credits, all consumers had net purchase from the grid under 200 kWh units for every month. Thus there was no purchase cost involved in NM-SDT. Further, consumers received compensation for unadjusted credits at the end of the settlement period. The amount gained from energy credits(AEC) is shown in fig16. The Annual savings is shown in fig19. In domestic tariff scheme without subsidy (NM-UDT), consumers had to pay fixed charges every month along with applicable electricity charges. All consumers except REC5 had to pay electricity charges in the month of September. REC3 received energy charges from the utility in January, July, and August as energy units produced from PV and accumulated energy credits could not compensate for energy demand. All other consumers had to pay only fixed charges from October to August. The purchase cost is shown in fig16.The compensation received for unadjusted credits was same as NM-SDT. The annual savings were proportional to annual benchmark costs(fig19). REC3 had the highest annual savings among five consumers as its annual benchmark cost was the largest. The purchase cost for REC3 was the highest (INR 4142), this was due to the undersized capacity of PV. As consumers received no electricity charges in several months, fixed charges played a dominant role in purchase costs. REC4 had the lowest purchase cost. The consumer had sanctioned load of 2KW and consequently the least fixed charges. All consumers had higher annual savings in UDT as compared to SDT. REC3 was the only exception. The difference in annual savings between SDT and UDT was inversely proportional to annual consumption. The consumers having less annual consumption (REC1,REC5) had more savings in UDT as compared to heavy consumers(REC2,REC3).

In Net metering with TOD, surplus PV units generated in any time block of a day is accounted as surplus energy generated in off peak hours. If these surplus energy units are not adjusted in power bill of current month, they are carried forward to next month. Fig 17 shows aggregated difference between hourly generated PV units and energy demand in all three time blocks of a day. It can be observed from the figure, there was higher frequency of instances when energy demand was more than generated PV units during off peak hours This was not surprising as off peak hours are between

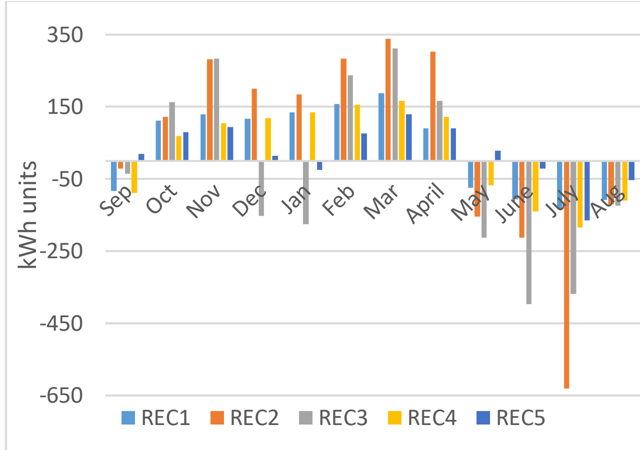

Fig14: Difference between hourly PV generated energy and demand in NM-SDT/UDT.

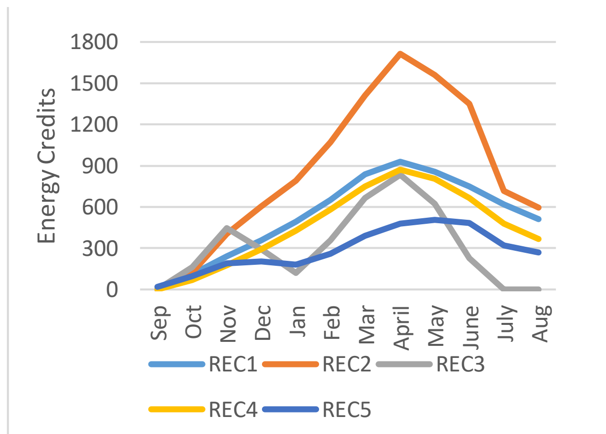

Fig15: Energy credits in NM-SDT/UDT.

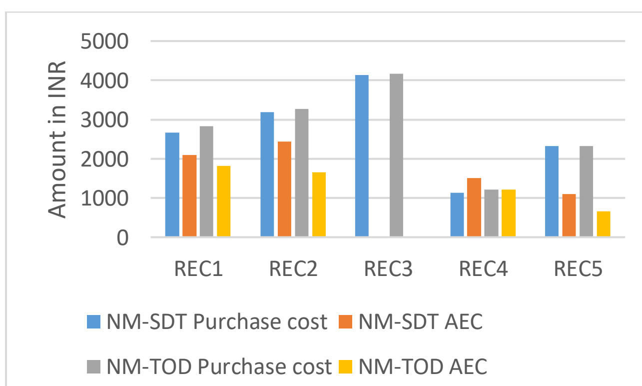

Fig16 : Purchase cost and amount gained from unadjusted credits in IPV.

4 AM and 10 AM where irradiation is usually low and energy demand is high. In TOD tariff, energy purchased from grid is charged at higher rate during peak hours. Therefore, reduction in energy import during peak hours has major impact on energy cost. Considering annual PV energy generated during peak hours and energy demand, all IPVs had surplus PV energy during peak hours. REC4 had the highest surplus generation over of 328 kWh units during peak hours followed by REC2 with 294 kWh units. REC3 and REC5 had lower energy surplus during peak hours with 48 and 55 kWh units respectively. All consumers except REC5 had no energy credits gained in September (fig18). In subsequent months, consumers had surplus energy credits. The purchase cost and the AEC followed the trend of NM-SDT.Annual savings in NM-TOD is shown in fig 19.

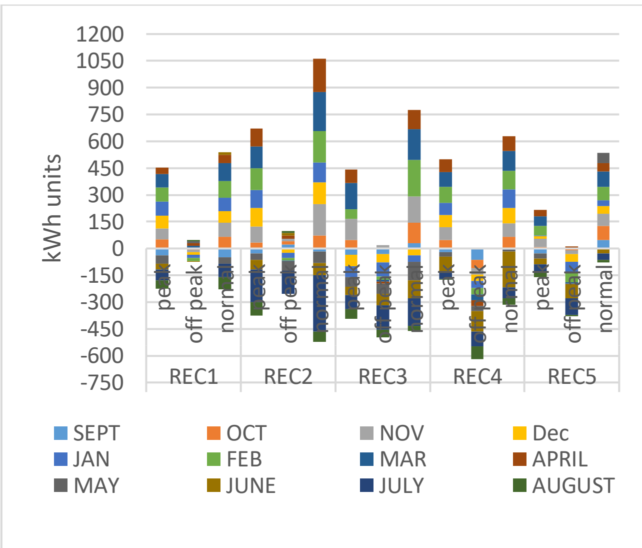

Fig17: Aggregated hourly difference between generated PV energy and demand in three time blocks in NM-TOD.

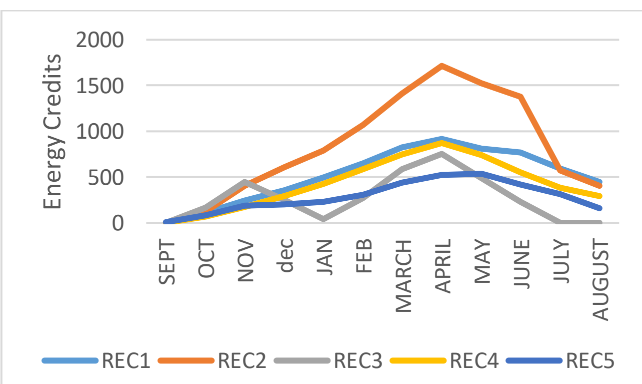

Fig18: Energy credits of consumers in NM-TOD

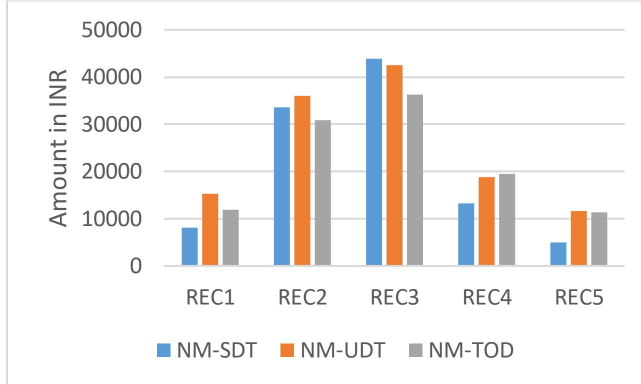

Fig19. Annual savings in IPVs.

3.2 Annual savings in ARPV

3.2.1 ARPV with VNM: In VNM all generated units from the 13.86 kWp PV system were sent to the grid. The distribution of share in generated PV energy among consumers was according to their annual consumption(fig8). The net difference between energy share and load demand for VNM-SDT/UDT is shown in fig20. The trend is like fig 14. An important development occurred in the case of REC3. The consumer had surplus PV energy in September. The shortfall in PV energy in July and august has decreased. All consumers had zero purchase costs in VNM-SDT. The consumers incurred purchase costs in VNM-UDT. The purchase cost of REC3 was smaller than NM-UDT (fig16&21). The purchase cost of REC1 and REC2 bincreased slightly. REC3 gained compensation for unadjusted credits (fig21). For other consumers, therewas fall in AEC. The trend in annual savings in SDT and UDT in VNM (fig22) remained similar to fig19. Consumers who had relatively smaller annual consumption, saved more in UDT. In VNM-TOD, all 5 consumers had annual surplus PV share during peak hours and normal time blocks of the day(fig23). The annual energy demand during off-peak hours surpassed PV energy share for all consumers. REC3, REC5 incurred only fixed charges in all 12 months. REC1, REC2, and REC4 had electricity charges in September. The annual savings in the case of VNM-TOD is shown in fig 22. The annual savings of consumers with exception of REC3, were lesser than IPV. This was mainly due to higher sum obtained from AEC in IPV. The monthly variation of energy credits of ARPV-VNM models is available in the appendix.

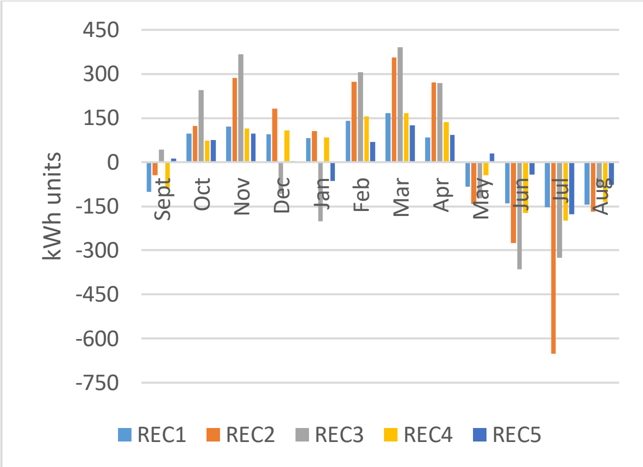

Fig20: Difference between share in generated PV energy and demand in VNM-SDT/UDT.

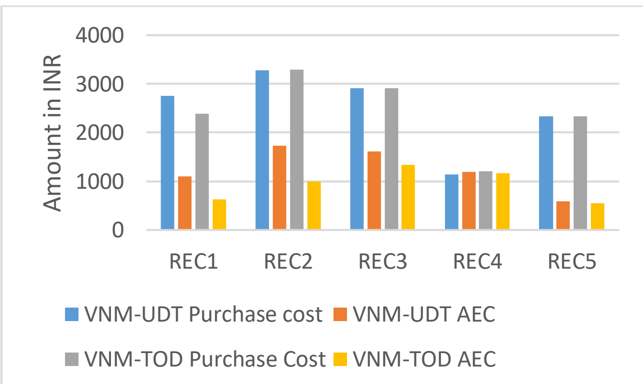

Fig21: Purchase cost and amount gained from unadjusted credits in VNM-UDT and VNM-TOD

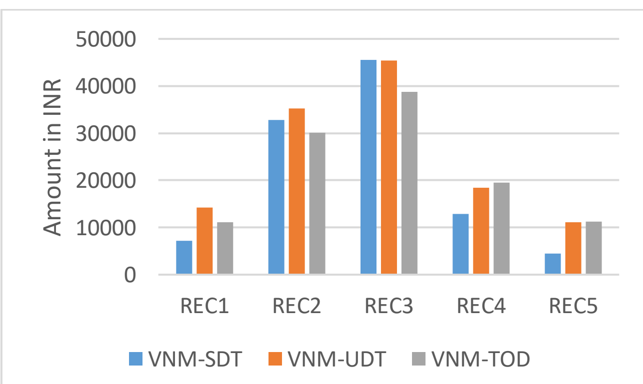

Fig22: Annual savings in ARPV -VNM models.

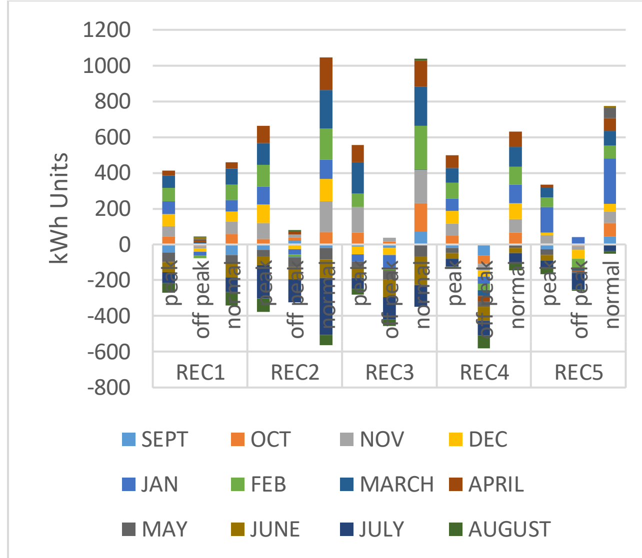

Fig23: Aggregated hourly difference between generated PV energy and load demand in three time blocks in VNM-TOD

3.2.2 ARPV with GNM: In GNM, the priority sequence for utilization of generated PV units to meet energy demand was from REC1 to REC5. In GNM, the energy credits are accumulated at the coalition level. The distribution of AEC among consumers was as per figure 8. In GNM-SDT/UDT, REC1, REC2, REC3, and REC4 did not purchase any energy from the grid for 12 months.REC5 had to import 159 kWh in September. For the remaining 11 months, REC5 did not have any energy purchase. REC1 and REC2 did not need to utilize any energy credits to compensate for their energy bills. Energy credits were utilized in four months period from May to August by REC3, REC4, and REC5. In GNM-SDT all users have zero power bills in whole year. In GNM-UDT, REC5 incurred electricity charges in September. For other months, REC5 only had to pay fixed charges. For all other consumers, the power bill had only fixed charges. The amount received for unadjusted credits was similar in GNM-SDT and GNM-UDT. In GNM with TOD tariff, the energy demand of REC1 and REC2 was fully met by energy units generated from ARPV for all time blocks of a day. REC3 had an annual shortfall of 168 kWh units in peak hours. Likewise, REC4, REC5 needed to purchase 464 and 496 kWh respectively from the grid during peak hours annually. REC1, REC2, and REC3 had to pay only fixed charges for the whole year. The energy credits were mainly used by REC4 and REC5. These consumers had lower priority and consequently faced a shortfall in available PV energy. REC4 had least purchase cost as the consumers has least fixed charge(fig24). Annual savings are shown in figure 25. In GNM, all consumers had higher annual savings than VNM-SDT. REC5 saved a slightly lower amount in GNM-UDT. In case of GNM-TOD, the two consumers at lower end of priority sequence (REC4, REC5) had lower savings with respect to VNM-TOD. The aggregated hourly difference of generated PV energy and energy demand is shown in fig 26.

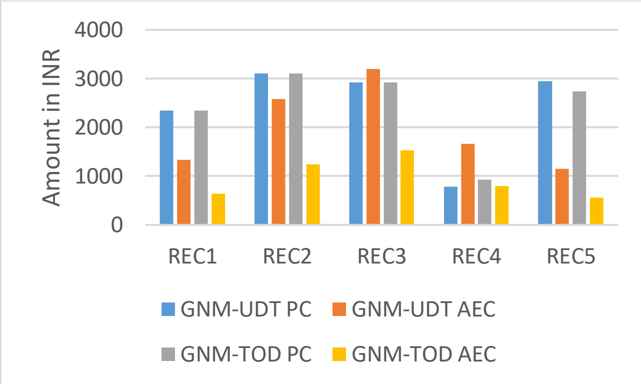

Fig 24: Purchase cost and amount gained from unadjusted credits in ARPV-GNM.

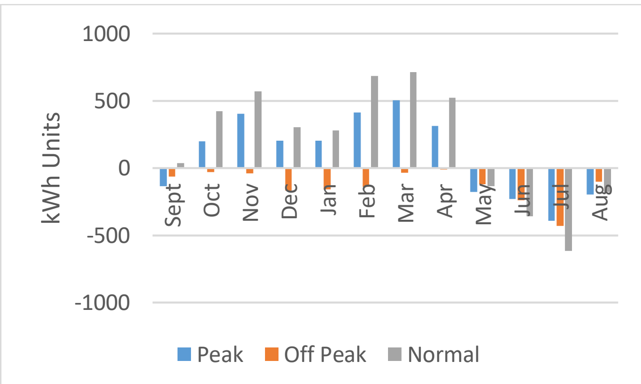

Fig26 The aggregated hourly difference between generated PV power and load demand in GNM-TOD.

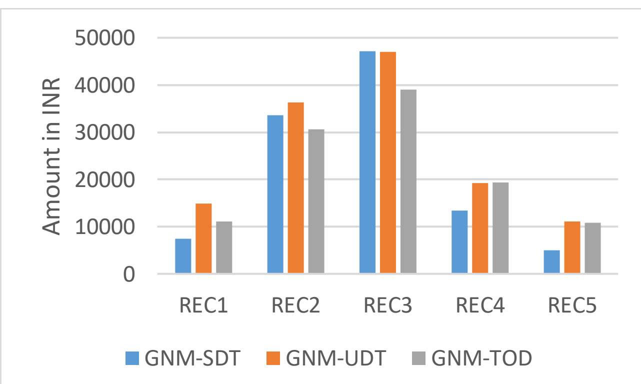

Fig26: Annual savings in ARPV-GNM models

3.2.3 Annual savings in proposed model

In the hybrid model, REC4 and REC5 paid at the rate of INR 3 per kWh for PV energy received from the ARPV. This amount was shared by three consumers. REC4 and REC5 continued to pay fixed charges and applicable electricity charges incurred to the DISCOMs. The annual savings were calculated in four cases: VNM-UDT, VNM-TOD, GNM-USD, and GNM-TOD. The PV share and energy credits received by the consumers in hybrid ARPV remained similar to ARPV models. That is, PV energy and AEC received by consumers in Hybrid-VNM models were same as VNM model. The annual savings of REC1, REC2, REC3 increased in the proposed model. The increase in savings was smaller in VNM cases compared to GNM. This was due to a relatively smaller contribution from REC4, REC5 in GNM. Annual savings for REC4, REC5 in the proposed model is shown in figure 28. The savings for REC4 and REC5 was due to reduced purchase cost and the amount received for unadjusted credits. These two consumers had higher annual savings in HGNM compared to HVNM. In VNM, REC4, REC5 paid for the fixed PV share. In GNM, the two consumers paid for PV energy which they utilized. Thus, purchase cost was lower in Hybrid-GNM for REC, REC5.

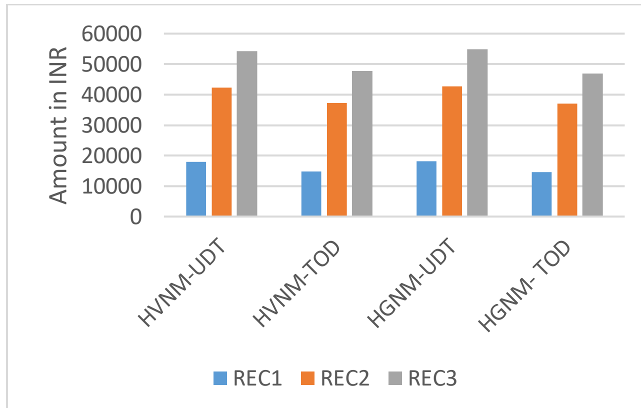

Fig27: Annual savings in Hybrid ARPV.

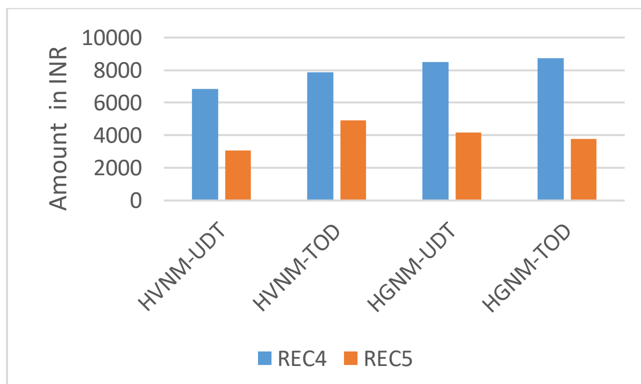

Fig28 . Annual savings for REC4,REC5

3.3 Life cycle cost :

Life cycle cost for PV system was obtained for all PV systems. The breakeven period and net annual savings after 20 years of project lifetime were obtained using the annual benchmark cost of energy as a baseline. The savings percentages were obtained as:

$$Saving\ \% = \frac{\text{Bechmark cost} - \text{life cycle cost}}{\text{Bench mark cost}}$$

Table 9: Breakeven period and savings after life time of project. BEV: breakeven period in years.

	REC1			REC2			REC3			REC4			REC5		
Cases	BEV	Saving	%	BEV	Saving	%	BEV	Saving	%	BEV	Saving	%	BEV	Saving	%
NM-SDT	13	114854	57.5	5	833594	81.1	4	1156955	79.6	7	263873	68.0	18	28870	22.6
VNM-SDT	9	116789	58.5	4	854423	83.2	4	1220428	84.0	7	279764	72.0	15	44370	34.7
GNM-SDT	9	124560	62.4	4	882496	85.9	4	1273036	87.6	6	295272	76.0	16	27874	21.8
NM-UDT	6	351465	67.1	5	917053	75.4	4	1110002	71.9	5	446166	73.4	6	250511	58.7
VNM-UDT	5	350235	66.8	4	934972	76.9	4	1214013	78.7	5	462188	76.0	6	266011	62.3
GNM-UDT	5	371629	70.9	4	968765	79.6	4	1266621	82.1	5	489435	80.5	6	229213	53.7
HVNM-UDT	6	425554	81.2	5	1080334	88.8	5	1394470	90.4	NA	225742	37.1	NA	101314	23.8
HGNM-UDT	5	434449	82.9	5	1090055	89.6	5	1417219	91.9	NA	281193	46.2	NA	137918	32.3
NM-TOD	7	237661	55.9	5	744316	69.4	5	902480	67.5	5	444942	68.9	7	223166	52.0
VNM-TOD	7	247598	58.2	5	765938	71.4	5	998290	74.7	5	499123	77.3	5	327383	76.3
GNM-TOD	6	249715	58.7	5	780388	72.8	5	1004937	75.2	5	493634	76.4	6	253942	59.2
HVNM-TOD	7	322851	75.9	5	911300	84.9	5	1178747	88.2	NA	260130	40.3	NA	162586	37.9
HGNM-TOD	7	312303	73.5	5	901281	84.0	5	1155039	86.4	NA	288699	44.7	NA	125552	29.3

Aggregation models (GNM, VNM) gave mixed results when compared with economic gains in IPV. Consumers in VNM had slightly higher gains compared with IPV. In GNM, the economic returns were higher than IPVs for consumers at the upper end of the priority sequence. The consumers ranked lower in priority had to purchase electricity from the grid, consequently had lower returns. This is noticeable for REC5. In subsidized tariffs, the time taken to reach the breakeven point was longer. This was especially seen in consumers with low annual consumption (REC5, REC1). Generally, consumers with lower consumption needed more time to reach the breakeven point. There is an interesting observation regarding subsidy. The subsidy in electricity tariff aims to reward consumers having low consumption. In non-subsidized tariffs, lower electricity consumers had more savings. For example, REC1 saved 58.5% of benchmark cost in VNM-SDT while in VNM-UDT savings increased to 66.8%. REC3 is the largest consumer among the five consumers. Its savings in VNM-SDT was 84.0 % while in VNM-UDT, savings was 75.23%. The possible explanation lies in the annual benchmark cost of consumers. Consumers with a large gap between annual benchmark cost in SDT and UDT have the potential to save more in UDT. REC3 was the biggest gainer in both VNM and GNM. In VNM, REC3 received the highest share of generated PV power while in GNM being at the upper end of priority rank, all energy needs were met by ARPV. Moreover, REC3 had undersized IPVs in net metering.

The proposed model gave the highest savings to REC1, REC2, and REC3 . The breakeven period was slightly higher for these three consumers as there was a larger initial investment. The economic gains for REC1.REC2 and REC3 in hybrid GNM were slightly smaller with respect to hybrid VNM. This was due to the smaller amount received from REC4, REC5. The proposed model showed that a consumer can have higher economic returns from ARPV by designing suitable terms of agreements. The load profile, share in the investment, distribution of generated PV output in VNM, rank in priority sequence and share in unadjusted energy credits at the end of settlement period in GNM should be considered by consumer for extracting higher gains from ARPV. Another significant result from the proposed model was financial gains for REC4 and REC5 without any investment. This may have an important consequence for consumers, especially from low-income groups. ARPV offers these consumers an opportunity to benefit from rooftop solar without need of investment .

4. Conclusion

In this paper, the economic feasibility of ARPV with respect to IPVs for domestic electricity consumers in Delhi was investigated. Semi-structured interviews were conducted with 5 domestic consumers of Delhi to obtain detailed hourly load profiles for every month. Based on annual energy demand and irradiance in Delhi, six PV systems were designed. There were five IPVs for consumers. The sixth PV system was ARPV which served the energy demand of all five consumers. Economic analysis was based on the hourly load profile of consumers, hourly generated PV power, tariff regulations of Delhi, and applicable investment costs present in the financial year 2020-21. The economic analysis was in terms of annual savings