Technical and Economic Analysis of Residential Photovoltaic Distributed Generation: Net Billing and Self-consumption in Peru

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Abstract- In Germany, Spain, Italy and other European countries, the promotion and development of distributed residential photovoltaic (PV) generation markets has been based mainly on the mechanism of regulated premiums by kWh generated - Feed in Tariff. The United States has employed the net metering mechanism. Both mechanisms have determined the price of the electricity injected to the grid energy be equal or higher than the grid electricity tariff. The accelerated cost reduction of PV technology has allowed, in diverse electricity markets, Grid parity. This circumstance has driven the revision and reformulation of the promotion mechanisms for distributed PV generation. This paper is a proposal to evaluate the net billing and self-consumption mechanism and the impact on the business sustainability of the distribution system operators (DSOs); as well as the economic incentive for the residential user to become prosumer. The mechanism has applied to the electricity retail market of Arequipa, located in southern Peru, with a specific solar potential higher than 2000 kWh/kWp. The results showed that: The subsidized electricity tariff for consumer less than 100 kWh/month, would not reach full grid parity before 2020. For consumer of higher than 100 kWh/month, the net billing and self-consumption mechanism allows the promotion of distributed PV generation. In addition, the under net billing, DSO would maintain their business sustainability. Finally, under the net billing mechanism the user will have the incentive not to oversize the grid-connected PV power.

Keywords Distributed generation, grid connected PV system, Incentives, Net billing.

1. Introduction

Nowadays, around the world, the renewable sources have a high importance for energy supply. In 2016, a 24,5% of consumption of electricity in the world was obtained from renewable sources which were installed with a power of 2017 GW. There are some several reason for this to happen, for instance: diversification of the energy matrix, security, decrease of technology cost of the supply and reduction of the environmental impact.

In 2018, the photovoltaic (PV) installed power worldwide was 505.5 GW. In 2017, wholesale electricity markets are responsible for 61% of the worldwide installed power whereas distributed generation represents 39% [1]. Fig 1.

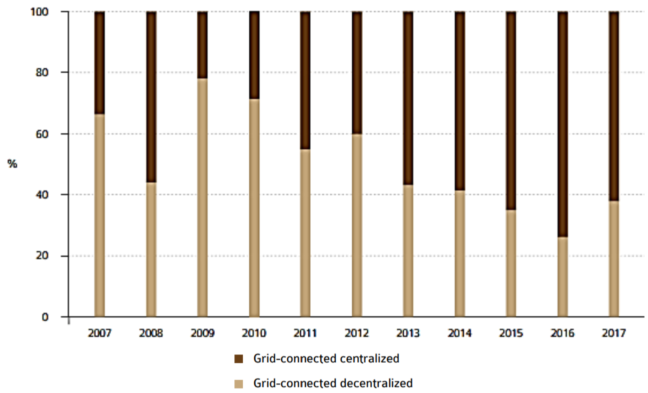


Fig 1. Installed PV power: Participation by type of installation, 2007-2017. Source: [1].

The markets of residential distributed PV generation have developed rapidly because of the promotion mechanisms which have allowed to what have the energy price of the prosumer to be stablish [2]. In this sense, the use of new technology for monitoring the production and consumption of energy has been fundamental for the development of more modern generation markets. Several of the studies developed allow us to see the advantages of monitoring solar station generation in real time and through platforms that have support in cloud computing [3][4][5][6][7][8]. Table 1 shows the promotion mechanisms for renewable energy generation characteristics more employed in different electricity markets [9].

Table 1. Mechanisms of promotion for renewable generation

Market	Mechanism	Characteristics
Wholesale	Auctions	Competitive process for contracting electricity supply. It allows to reveal the real price of generation.
		Power (MW), energy (MWh) or both is tendered. According to characteristics each market.
Wholesale and distributed generation	FiT	Provides security of contract for a long-term: Profitability.
		The whole volume energy is sold to the defined price in the purchase agreement, which is higher than the market price.
Distributed generation	Net metering	Physical balance. The energy injected into the grid is compensated at the retail Price.
		Simple scheme to administer using bidirectional meter.
Distributed generation	Self-consumption	Production that is consumed in real time, is not counted and billed. Compensation by exceedances do not exist.
Distributed generation	Net billing	Economical balance. The energy injected to the grid is compensated to a lower price than the retail price. It requires a meter that register energy flows separately.
Wholesale and Distributed generation	Subsidies of capital	Direct financial subsidies aimed at reducing the initial, partially or totally cost barrier of the system.
Wholesale and generation distributed	Renewable Portfolio Standard	Mandatory requirement for electricity distributors to electricity supplies from renewable energy.
Distributed generation	Sustainable Building Requirement.	Requirements in new buildings (residential and commercial) for the use of renewable energy and energy efficiency.
Source: Elaboration in based on [1], [2], [].		

The article is organized as follows: chapter 2, a literature review is made of the effects that the net metering, net billing and FiT in the electricity markets have generated. In chapter 3, formulation of the grid parity analysis is described, as well as the basic concept and the mathematical formulation of the promotion mechanism net billing and self-consumption, considering the economic profit, the optimal PV power for the user and the impact in the business sustainability of the electricity distribution company (DSO). Later, the characteristics of the energy demand of the users is described, by monthly consumption range, and the available solar resource for the geographic area of Arequipa, to use it as a study case. Chapter 4 details the results obtained from the application of the net billing to promote the distributed PV generation. Finally, in chapter 5 the conclusions are described.

2. Analysis of the promotion mechanisms for distributed generation.

The promotion mechanisms are designed in function to the level of incentive for the user, the PV technology cost and the available solar resource. Under the FiT and net metering mechanisms that have promoted the distributed renewable generation in Europe and USA, the DSO are forced to purchase the excess of PV energy of the prosumers, even though the energy price in the electricity wholesale market is more economical. Because of this, it has generated an implicit subvention, reflected in increases of price and subsidies crossed that are assumed by the users that have not integrated PV systems, as well as losses of business sustainability of the DSO. In Figure 2, showed a simplified diagram of the relation between wholesale and retail prices and the participation in the distributed generator.

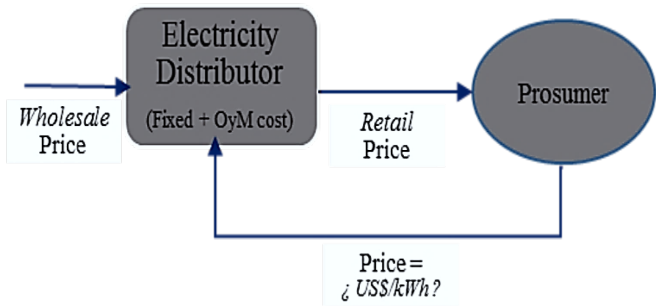


Fig 2. Simplified diagram of the electricity market and the distributed generator. Source: Own Elaboration

The implicit subventions of the integration of residential PV generation have been evaluate in [10] that analysis establishes the mathematical formulation of the net metering like an alternative mechanism to the FiT existent in Spain. In [11, 12, 13], it is evaluated the impact of the net metering in the sustainability of investments made by the DSO and the increase of the final electricity tariff, because of the high penetration of distributed generation. In [14,15] it is presented the impact of the net metering on the recovery costs of electricity infrastructure and crossed subsidies that are produced by the prosumers. In [16], it is based in microeconomics models, they present a comparative analysis of the FiT, net metering, net purchase and sale, showing that if the PV price energy has the same value of residential one, the mechanisms do not change in their operation and produce the same incentive to the user. In [17] it evaluates the impact of net metering in Cyprus in relation to the economic income of the DSO, showing that the self-consumption is a sustainable mechanism for the promotion of the distributed PV generation. In [18] it is studied the transition of the FiT to the net metering in Italy, justifying this replacement for having reached the grid parity in residential market.

In the Figure 3, shows the reduction of the investment costs of the different components and services associated to the installation of PV systems, experienced between 2016 and

2017. Therefore, to measure the penetration increase of the PV energy in the electricity markets and reduce the PV technology cost, is necessary to have dynamic politics that allow the revaluation and reformulation of the promotion mechanisms applied [19],[20]. Table 2 shows the different regulation in some countries and its more remarkable characteristics.

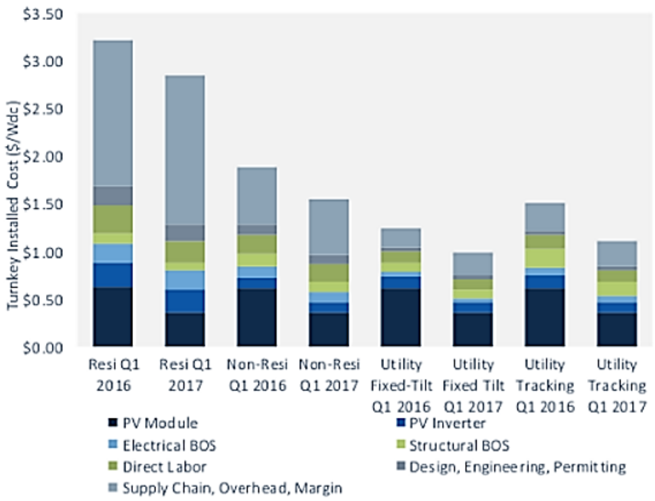


Fig 3. Evolution of the investment costs in PV systems between 2016 and 2017. Source: GPM Research 2017.

The trend of competitiveness of the PV energy price with respect to the conventional supply has been studied in [21], which explains that the grid parity conditions are being generated in the residential market in several diverse countries. In [22] it analyses the necessary conditions for the grid parity in Italy and Germany, analyzing of curves PV generation and consumption. In [23] It evaluates the LCOE in Malaysia to compare it with the regulated prices established for promotion of residential PV generation. [24] presents a dynamic model of grid parity in different European countries and different groups of consumers. In [25] it is evaluated the grid parity in function of the analysis of curves of experience for the prediction of PV energy prices and his comparison in relation to the wholesale and retail price in Germany.

The grid parity in some electricity markets shows that the self-consumption of PV energy is a tool to optimize for the promotion of the residential PV generation. Finally, recent studies [26],[27],[28], show that the payment of the injected energy at a lower value than the final price under the potential net billing mechanism – is based on the existence of a high solar resource and the current conditions of PV technology costs.

Table 2. Promotion mechanisms for distributed PV generation.

Geographic region and Country		**Year**	**Mechanism**				**Solar resource, kWh/kWp**
			FiT	**Net metering**	**Net billing**	**Others**	
North America	U.S. California	2000	-	Active	-	-	1800
Europe	France	2004	Active	-	-	Investment subsidies	1100
Europe	Germany	2004	Active	-	-	Investment subsidies and self-consumption	900
Europe	Italy	2005	Inactive (2013)	Active	-	Investment subsidies	1300
Europe	Spain	2007	Inactive (2011)	In evaluation	-	Investment subsidies	1500
North America	Mexico	2010	-	Active	-	-	1800
North America	U.S. Alaska	2010	-	-	By surplus energy at the avoided generation cost	-	800
Latin America	Brazil	2012	-	Active	-	-	1400
Caribbean	Barbados	2013	-	-	By net volume energy, at the wholesale generation cost	-	1300
Latin America	Chile	2014	-	-	By surplus energy to the avoided generation cost	-	2000-2400 (North)

Source: Elaboration based on [10], [11], [29], [30], [31], [32], [33].

In the recent years the net billing is applied in several countries. The policies that the already mentioned countries have adopted allow the consumer to be more schematically involved.

In [34] a tariff scheme is presented using net billing for the city of Rome in which an annual net of energy consumption is proposed. The amount presented for billing is based on a minimum average and maximum cost of energy sales without considering the amount of transportation and distribution. The purpose of conducting an annual netting is that it allows the consumer to have a better observability of the return on investment.

3. Methodology

As follows, this article presents the next methodology:

3.1. Energy performance madel of the PV system

Next, it is presented the energy Performace Ratio, PR, which has reference to the real energy efficiency against the energy theoretical possible, independently of the PV system orientation.

$$PR = \frac{Epro_i/Pp}{Irr_i/Gstc} \quad (1)$$

Where $Epro_i(kWh)$ is the energy produced with the $Pp(kWp)$ installed power, $Irr_i\,(kWh/m^2)$ is the global horizontal irradiance, $Gstc\,(kW/m^2)$ is the irradiation measured under standard conditions.

As a result the energy production is:

$$Epro_0 = \frac{Pp\, Irr_i\, PR}{Gstc} \quad (2)$$

The PVWatts model by NREL (National Renewable Energy Laboratory) estimates the value of Performance Ratio of grid connected PV systems regarding different factors, like:, the level of losses in the wiring, PV inverter DC/AC efficiency and environmental conditions. The Table 3 shows the parameters and factors for calculating energy production in this study.

Table 3. Technical parameters.

Parameters	Acronym	Percentage
Inverter efficiency	ninv	95.0%
Conductivity wires efficiency	ncc	97.0%
Performance Ratio	PR	85.0%
Lost by environmental conditions	np	5.0%
Annual degradation rate	D	1.0%
Analysis period in years	T	20

Table 4. Effect of degradation rate and performance requirement on PV system life.

Degradation rate	Time of life 80% Pmax (Years)	Time of life 50% Pmax (years)
0.20%	100	250
0.50%	40	100
0.60%	33	83
0.70%	29	71
0.80%	25	63
1.00%	20	50

Source: [29]

The production of PV energy every year follow, relates with the degradation rate. Table 4.

$$Epro_i = Epro_0\,(1-d)^i \quad (3)$$

Where d: Degradation rate, %.

3.2. Grid Parity model for PV energy price

It has posed the analysis of the grid parity from the point of view of the final user, whose alternative are to buy electricity to retail tariff or self-consumption PV electricity, with the indicator Levelled Cost of Electricity (LCOE). The indicator LCOE is a measure mint of the energy cost during the life cycle of the PV system. [29]

$$LCOE = \frac{Cpp + \sum_{i=1}^{T} \frac{Coym_i}{(1+r)^i}}{\sum_{i=1}^{T} \frac{Epro_i}{(1+r)^i}} \quad (4)$$

Where Cpp: Investment cost $US\$$, $Coym_i$: Annual OyM cost in $US\$$ and r: Interest tax in %.

The energy sale factor k', necessary to motivate the user to install a PV system is:

$$k' = \frac{LCOE}{p_{BT5B}} \quad (5)$$

Where p_{BT5B}: Energy final price, $US\$/kWh$

3.3. Net billing and self-consumption mechanism model.

Base on the model posed in [26, 27], under a net billing mechanism, the injected energy price is less than electricity final tariff.

The residential user that covers his consumption by the electricity grid, without PV system, will have the electricity billing according to:

$$F1_i = Ebase_i\, p_{BT5B} \quad (6)$$

Where $F1_i$: Electricity billing without PV system in a year i, in $US\$$. $Ebase_i$: Energy consumed in the year i, kWh. The values are shown in Table 5.

When the user installs a residential PV system, he becomes a prosumer and his electricity billing corresponds to:

$$F2_i = Ecom_i\, p_{BT5B} - Even_i(k\, p_{BT5B}) + a_{inv}\, Cpp \quad (7)$$

Where $F2_i$: Electricity billing with PV system in the year i, in $US\$$. $Ecom_i$: Energy purchased from the grid, kWh. $Even_i$: Energy sold to the grid in kWh. a_{inv}: Annual Investment factor, 1/ year.

The net billing mechanism requires that it fulfils the condition: *k<1*

Figure 4 shows that the purchased energy, corresponds to the periods *t*, where the production is less than the consumption.

$$Ecom_i = \sum_t^i (Ebase_t - Epro_t); \quad (8)$$

$$if\ (Ebase_t - Epro_t) > 0$$

The net sale of electricity corresponds to the periods *t*, where the production is higher than the consumption. Fig. 4.

$$Even_i = \sum_t^i (Epro_t - Ebase_t); \quad (9)$$

$$if\ (Epro_t - Ebase_t) > 0$$

The relation between the generated and consumed energy, without PV system, is considered like a base case and permits to define a coverage rate.

$$\beta = Epro_t / Ebase_t \quad (10)$$

Self-consumption of PV energy is the area of the production that intersects with consumption, energy is consumed locally. Self-consumption rate is expressed in base on the total PV production.

$$\alpha = (Epro_t - Even_t)/Epro_t \quad (11)$$

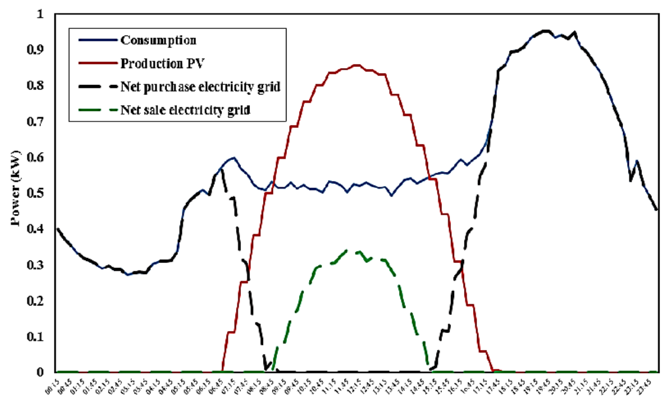


Fig. 4 Typical a residential electricity consumption and PV production behaviours.

The optimal power installed PV minimizes the costs that incurres during the useful life of the project.

$$\min\left(\sum_{i=1}^{T} F2_i/(1+r)^i\right) \quad (12)$$

The user profits, by the production of PV energy is made up of the economic valorization of the instantaneous self-consumption and of the surplus energy.

$$BenNetBill = \sum_t^i (Epro_t\, \alpha)\, p_{BT5B} + \sum_t^i Even_t\, k\, p_{BT5B} \quad (13)$$

The present model, from the perspective of the DSO, establishes the restriction that the PV price energy is not higher than the energy price that could be purchased in the wholesale market to supply his customers. [16]

$$k\, p_{BT5B} \le p_{em} \quad (14)$$

Where p_{em}: is the energy price in the wholesale market, $US\$/kWh$

It defines the indicator, *% Impact DSO*, like the relation of the economic impact over the DSO respect with to the electricity billing without project.

$$\frac{ImpactDSO}{Facturación_{S/P}} = \left|\left(\frac{\sum_t^i Even_t\,(k\, p_{BT5B} - p_{em})}{Ebase\; p_{BT5B}}\right)\right| \quad (15)$$

Finally, it formulates the indicator Payback, like the time in years of recovery of the initial economic investment of the project.

$$P/B = \frac{C_{Pp}}{BenNetBill} \quad (16)$$

3.4. Supply and demand energy data of the study case

The evaluation of the impact of the net billing and self-consumption mechanism was made for the residential photovoltaic integration in Arequipa region which is located in the south area of Peru. The information of the available solar resource has estimated in terms of the energy performance of a PV system, geographically near the analysis zone, from the monthly energy real production and installed power. Also, it compares with the NASA information-SolarGis database. Fig 5.

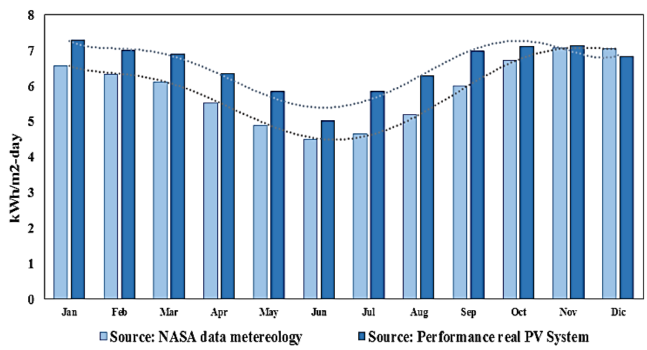


Fig. 5: Solar Radiation horizontal in Arequipa, Peru.

For the grid parity analysis, it has been considered that the PV system has an optimal inclination angle []. The energy production will have a maximum value of 2300 kWh/kWp and a minimum of 1945 kWh/kWp.

The typical profile of electricity consumption is shown in terms of the relation between the instantaneous power demand over the peak demand. Fig 6.

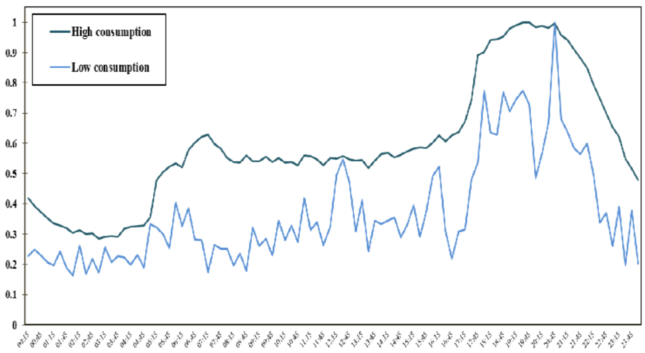


Fig. 6 Energy demand profiles p.u. (Pinstataneous/Pmax). Source: Estudios de Caracterización de Carga – SEAL ST2 2013.

In the Table 5, a typical monthly consumption, by range of consumption is showed. The high consumption household, who use more than 150 kWh/month, with a higher load factor 0.59 and low consumption users have less than 150 kWh/month, it is estimated with a load factor equals to 0.37.

Table 5. Energy consumption data by consumer range.

Consumption range kWh/month	Average consumption kWh/month
< 1 : 30>	11.7
< 31 : 100>	70.9
< 101 : 150 >	119.0
< 151 : 300 >	192.3
< 301 : 500 >	350.2
< 501 : 750 >	566.5
< 751 : 1000 >	834.3

Source: Osinergmin, Data 2015.

The flat rate price for residential end-user it reflects the added cost of generation, transmission and distribution of electricity. The Fund for Electricity Social Compensation, FOSE, intends to promote electricity access to all residential customers whose consumption is lower than 100 kWh per month and to promote private investment in rural electrification systems under 20 MW. FOSE operates as a cross-subsidy, in which the consumer only pays 20% of the actual tariff (which is based on the cost of generation). The electricity tariff for the end user is subsidized by charging a special tax on electricity bills of people whose consumption is higher than 100 kWh/month. Table 6 shows the final user's energy prices without apllying of FOSE.

Table 6. Electricity prices in US$/kWh.

<0:30> kWh/month	<31: 100> kWh/month	> 100 kWh/month	Without FOSE	Wholesale market
0.119	0.147	0.163	0.158	0.078

Source: Osinergmin, Data 2015.

4. Results

In this section, the evaluation results of the net billing introduction and self-consumption mechanism, like the motivation to promote the distributed PV generationis is showed. The analysis is presented in Arequipa, a representative city at the south of Peru, with a high level of solar irradiation.

In the Figure 7, the grid parity analysis shows that a user that invests in a PV system will have profits – a positive net current value positive -, if the final price is higher than LCOE. Thus, doing a trend scenario to reduce the PV technology costs, it shows that because of the effect FOSE the users of lower consumption to 30 kWh/month even do not reach the complete grid parity. For users of consumption between 30 and 100 kWh/month, the grid parity will reach before the 2020. The users that consume more than100 kWh/month, there will be a greater motivation to integrate themselves PV systems. It can be noted that in a scenario of non-application of the FOSE, for any user it would result more convenient to produce and self-consume PV electricity. In a horizon between 2015-2025, the net billing mechanism of the PV energy is sustained less than the retail tariff value.

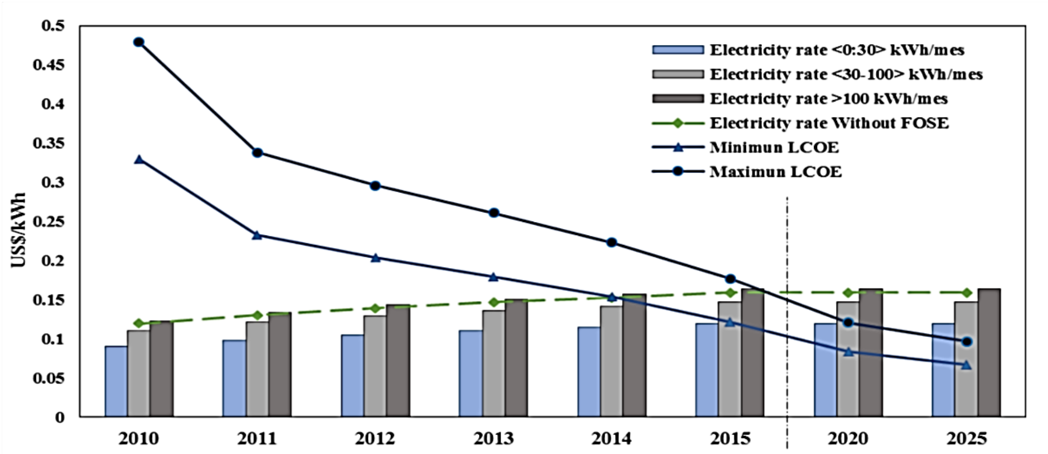
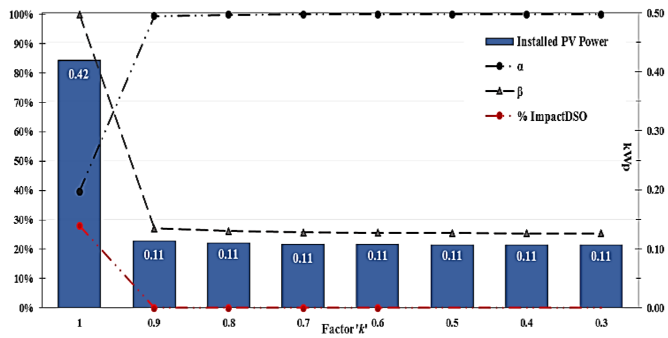
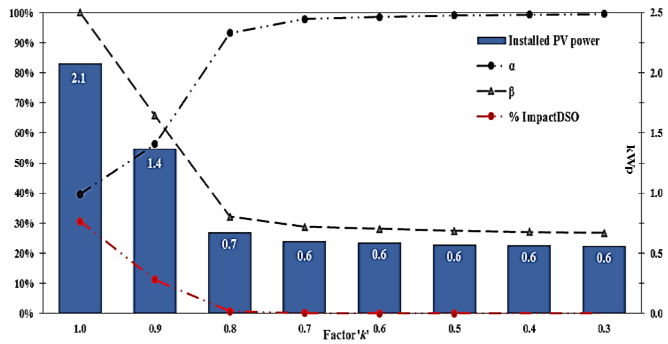


Fig. 7 Grid Parity analysis in the residential market.



a) Prosumer with consumption <31-100> kWh/month



b) Prosumer with consumption <301-500> kWh/month

Fig. 8 Impact of the sale factor *k* in optimal PV power.

Figure 8.a) and 8.b), for the prosumer with consumptions between 30 and 100 kWh/month and between 300 and 500 kWh/month respectively, has been considered the current investment cost of 2210 US$/kWp. It presents the impact of the economic value of the injected energy, in terms of the optimal PV power, self-consumption rate, coverage rate and impact to the DSO. It shows that the lower payment by the PV energy incentive there´s no oversizing of the PV system in relation to the net metering mechanism. For the specific case of $k=1$, equivalent to net metering mechanism, the optimal PV power is 0.42 and 2.15 kWp, respectively, that covers all the demand of the user by each consumption range (coverage rate 100%). The lower factor *k* allows the reduction of the optimal sizes to 0.1 and 0.6 kWp, respectively. Also, the payment by the energy injected to a value of 80% of the retail price attenuates the *% Impact DSO* rate near to 0%. This is due to the reduction of PV system, therefore, while a less energy is produced and a less payment by the PV energy is injected. The lower impact to the distributor is related with lower coverage rate and high self-consumption rate.

Under the approach of business sustainable scheme for the DSO, the maximum payment for the PV energy (Eq.14) must not exceed 49% of the final tariff. The remaining percentage corresponds to the payment of fixed and O&M (Operation and Maintenance) costs. (Fig.2)

Figure 9.a, with this sale factor $k=0.49$, the user with consumption between 31 and 100 kWh, with investment cost of 2210 US$/kWp will not get any incentive to become prosumer, so it will continue to be covering all his consumption with the electricity grid. By the investment cost of 1800 US$/kWp and installed PV powers until 0.25 kWp, the user will gain an economical benefit.

Figure 9.b, for user with an electricity consumption between 301 and 500 kWh/month, the optimization process shows that the prosumer will have profits that exceed its condition of consumer with PV power from 0.1 to 0.9 kWp (*VPN Without PV system> VPN with PV system*), being the optimal power (*Minimum VPN with PV system*) of 0.6 kWp to investment cost 2200 US$/kWp. PV systems, with higher powers than 0.6 kWp, do not generate incentive to become residential prosumer. It shows, also that self-consumption rate higher than 75% generates the greater profits, related to coverage rated less than 30%. The consumption of the prosumer will depend on the electricity grid in 70%. The reduction of the investment cost to 1800 US$/kWp increases the range of convenient PV powers to the user between 0,1 and 1.75 kWp, being the optimum PV power of 0.8 kWp, with coverage rate by the PV system of 45%. Therefore, 55% of the consumption will have to be supplied by the electricity grid. The trend of the indicators analyzed, is similar for the other consumers, being the users with consumption higher than 100 kWh/month, who have greater incentive to become prosumer, with higher PV power.

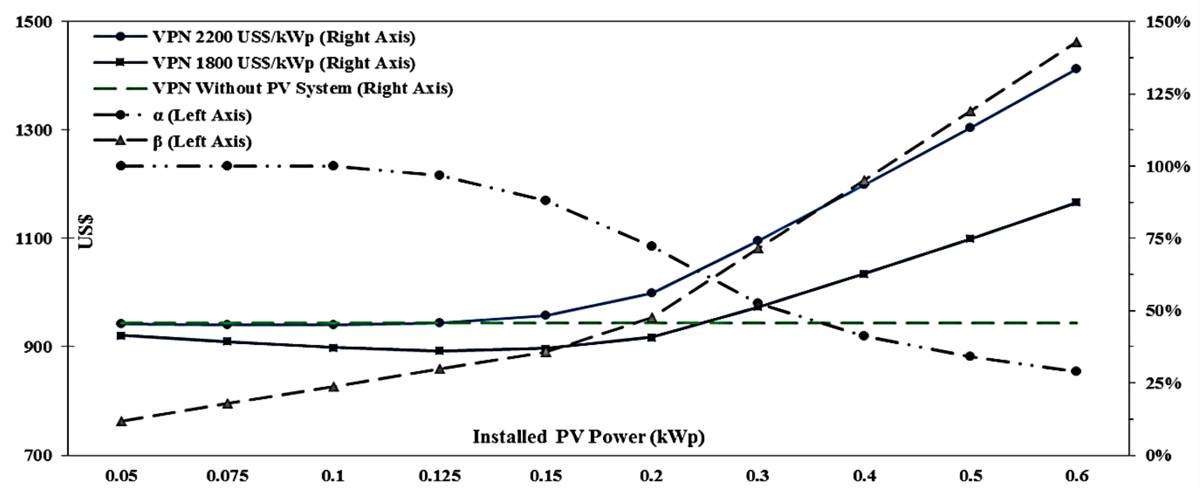
Table 7 and 8, shows the optimal installed PV powers for the conditions of net metering and net billing with $k=0.49$. In addition, the maximum PV power which fulfil that *VPN without PV system > VPN with PV system.*

Table 7. Optimal installed PV power (kWp) – Investment cost 2210 US$/kWp.

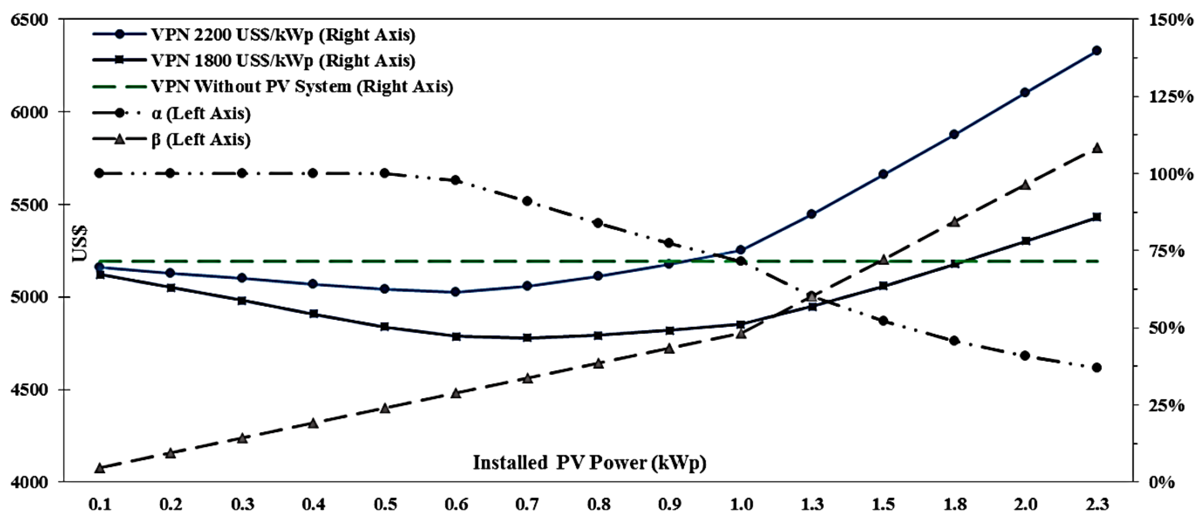
Consumption range kWh/month	*Net metering k=1*	*VPN Without PV system> VPN with PV system*	*Net billing k=0.49*
< 1 : 30>	0.1	--	--
< 31 : 100>	0.4	0.1	0.1
< 101 : 150 >	0.7	0.3	0.2
< 151 : 300 >	1.1	0.5	0.3
< 301 : 500 >	2.1	0.9	0.6
< 501 : 750 >	3.4	1.5	0.9
< 751 : 1000 >	4.9	2.3	1.4

Table 8. Optimal installed PV power (kWp) – Investment cost 1800 US$/kWp

Consumption range kWh/month	*Net metering k=1*	*VPN Without PV system> VPN with PV system*	*Net billing k=0.49*
< 1 : 30>	0.1	--	--
< 31 : 100>	0.4	0.25	0.15
< 101 : 150 >	0.7	0.6	0.3
< 151 : 300 >	1.1	1	0.4
< 301 : 500 >	2.1	1.75	0.8
< 501 : 750 >	3.4	3	1.1
< 751 : 1000 >	4.9	4.3	1.6



a) Prosumer with consumption <31-100> kWh/month



b) Prosumer with consumption <301-500> kWh/month

Fig. 9 Optimal installed PV power - *net billing* k=0.49

5. Conclusions

In this article, the assessment of net billing and self-consumption mechanisms under the conditions of the residential market of Peru is presented. In first instance it showed that the residential user will have greater economic incentive while the difference between the final price and the LCOE is higher. Therefore, the users of higher consumption than 100 kWh/month, with grid parity, self-consumption of PV energy would result more convenient. Household users with consumption less than 100 kWh/month, would not reach the grid parity complete before the 2020.

It showed that *net billing* mechanism designed, with the sale factor for the PV energy is equals to 49% of the final tariff, it generates a reasonable motivation for the integration of PV systems, that cover the consumption of the prosumer near to a 30%, at an investment cost of 2200 US$/kWp. For an investment cost of 1800 US$/kWp, the PV systems with greater economic profit allow a coverage rate of 45a%.

To the electricity distribution company, with a purchase price of the PV energy near to a 50% of the final tariff, will guarantee his business sustainability. The PV energy purchased to the prosumer will be able to redistribute it in the market.

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