Analysis of the penetration potential of PV Microgeneration in Uruguay

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***Abstract*—In the last few years there has been an increasing incorporation of solar photovoltaic generation in the Uruguayan energy matrix. This paper focuses on the subject of photovoltaic microgeneration connected in the low-voltage network. The aim of this work is to establish an adequate methodology to estimate microgeneration potential in Uruguay. Towards that end, simulations were carried out in softwares *Power Factory* and *SimSEE* in order to evaluate the impact this form of generation has on the Uruguayan Electrical System, regarding both technical and economical aspects.**

***Index Terms*—Photovoltaic Microgeneration, Impact on low-voltage network, Generation Cost**

I. Introduction

Decree 173/10 regulates microgeneration in Uruguay since 2010. It allows clients from the state electricity utility UTE to connect renewable sources of energy to the low-voltage distribution network [1]. Currently, the total capacity of photovoltaic microgeneration in Uruguay is $15.27\ MW$ [2]. Most of microgenerators are companies. This is explained by the fact that it is still not economically convenient for households to have microgeneration. Companies, however, have additional benefits through a reduction of taxes.

The process of incorporation of microgenerators to the energy matrix of Uruguay supposes changes in several aspects. First, this process results in a change of roles, the client has the possibility of self-consumption, and can even become energy suppliers. On the other hand, regarding network technical aspects, these new distributed generators will alter parameters that should be taken into account when proposing sustainable incentive policies.

This paper is part of the project "Photovoltaic Microgeneration in Uruguay: benefits, regulatory framework and production of local capacities" financed by the National Agency of Research and Innovation. The purpose of this project is to evaluate the impact large deployment of microgeneration might have on the network, as well as on the electricity utility billing.

In addition, the system's economy is disturbed by the incorporation of this new form of generation; expensive sources are replaced by a renewable, fuel-cost free source of energy. However, the economic incentive, which is faced by the country, might modify generation costs greatly with a large incorporation of microgeneration.

This work aims to design a methodology to determine the potential of microgeneration in Uruguay. In order to accomplish this, limits to microgeneration's expansion have to be found. Those limits are determined by the impact introduced by microgeneration.

From the technical point of view, the change in network configuration produces effects in the voltage profile, in electrical losses and in the performance of protection devices; having single-phase generators alters the phases balance; the inverter, used for the connection with the grid, may cause an increase in harmonic distortion of the current and voltage. All these factors limit the expansion of microgeneration and therefore have to be studied.

A literature revision was carried out and several examples of technical impact studies were found. In [3] three different types of European low-voltage distribution networks with distributed generation were studied by power flow calculations; in this paper different magnitudes, such as voltage profile and branches current, among others, were evaluated for different load and generation scenarios varying also the position of the generator. The evolution of power losses with the incorporation of microgeneration is considered in [4]. On the other hand, the change in losses due to unbalance of single-phase load and generation is studied in [5]. Finally, in [6] a maximum of PV generation is found regarding power quality as the upper level of voltage total harmonic distortion is reached for a certain level of penetration.

Another important feature is the change in energy dispatch due to the increasing amount of self-dispatchable sources, that results in a change in the generation cost.

The paper is structured as follows. In Section II we present the methodology used for our analysis, which considers both the technical aspects and the economic studies. In Section III we present the results of the technical study while in Section IV the results of the economic study are presented. Finally, Section V is for the conclusions of our work.

II. Methodology

A. Technical impacts on the low-voltage distribution network

This part of the work focused on the evolution of electrical losses and load in lines, voltage at connection points of clients, and load of the distribution transformers.

The procedure consisted in the performance of load flows using the software *Power Factory* of DIgSILENT GmbH [7], and it was applied to three different typical networks found in Uruguay, a rural, an urban and an industrial one. Networks' characteristics, such as single-line diagrams, data from lines and transformers, and the demand curve, were provided by UTE.

Since the behaviour of the installations of interest, based on photovoltaic generation, are time and season dependent, quasi-dynamic simulations were performed through an entire year with a time step of one hour. The demand curve of each client was constructed regarding the total demand curve and the contracted power, whereas the generation curve was obtained through the software PVsyst [8].

Each consumer has its own photovoltaic generator associated, whose capacity is less or equal to the contracted power of the consumer [1] [9]. In order to simulate different scenarios of penetration, the capacity of the generators were varied from 0% until 100% of the contracted power, with steps of 10%. For each level of penetration, voltage levels, losses and load were recorded. As an example, the single-line diagram of the rural network is shown in Fig. 1.

To sum up, the procedure we followed in order to study the technical impact is:

1) Model different kinds of distribution networks in a power flow programme.
2) Assign to each load a photovoltaic generator.
3) Performe power flow simulations through an entire year with a time step of one hour.
4) Record the values of voltage at connection points, losses in lines and load in lines and transformers.
5) Compare with the original case with no microgeneration and with the range of acceptable voltage according to Uruguayan Regulatory Authority.
6) Repeat the procedure varying the level of penetration changing the capacity of generators from 0% until 100% of the contracted power, with steps of 10%

B. Economic study

The change in generation dispatch was simulated in software SimSEE [10] and the cost of generation was calculated for different levels of penetration.

The cost of photovoltaic microgeneration was calculated taking into account the following aspects: first, a reduction of the power demand is produced since the microgenerator supplies the load which is connected to, and there is no positive contribution to the generation cost; if there is a surplus of power, this will be used to supply the rest of the demand and will be remunerated. Consequently, the cost of the surplus of energy is added to the cost calculated by SimSEE.

The payment received by the microgenerator corresponds to the energy injected into the grid valued at its client tariff. This is why it is important to analyse different kinds of clients with different tariffs. In the present case of study, three Uruguayan types of clients, with their respective tariffs, were considered. The approach followed in this part is different from the technical study, since the networks introduced before are not used. Instead, the total number of clients with specific tariffs are considered; this study is, therefore, on a bigger scale than the technical one. The demand curves of the studied clients are scaled versions of those of the networks from the technical study.

In the following we summarize the steps of this study:

1) Using software SimSEE the Uruguayan Electrical System is elementary modelled as four nodes with their respective demand curves.
2) Three of those nodes represent different kinds of clients with their respective tariffs. To these nodes, photovoltaic microgenerators are connected.
3) For different levels of photovoltaic penetration, the optimal generation dispatch is simulated for a whole year.
4) The total annual cost of generation is calculated by the programme without taking into account the microgeneration.
5) The annual cost of microgeneration is calculated as the energy injected from the nodes with microgenerators to the rest of the system, valued at the considered tariff.

III. Results of the technical study

In this section relevant results of the executed load flows are presented.

A. Voltage profile

In relation to voltage profile, it was found that for a large deployment of microgeneration, in residential networks,

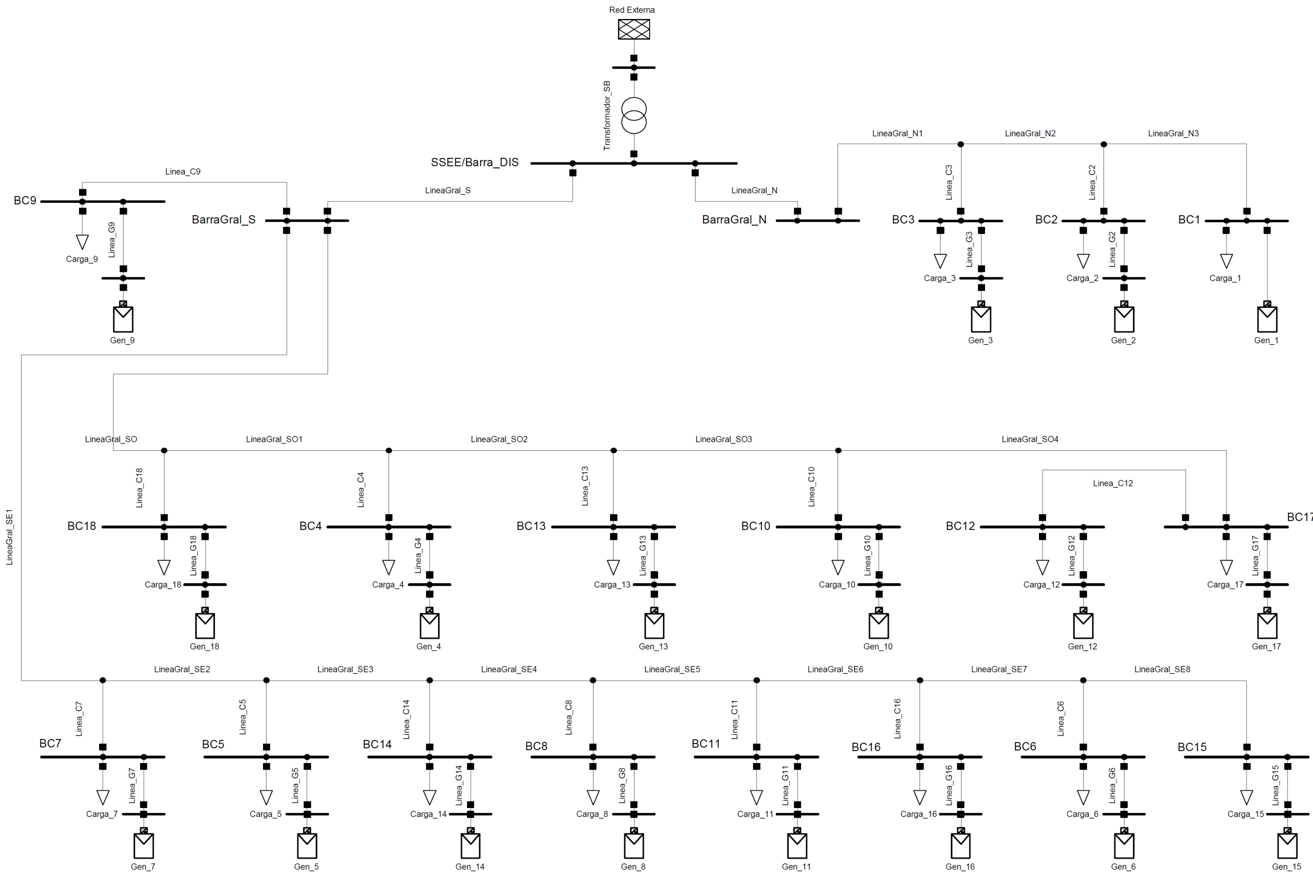

Fig. 1. Single-line diagram of the rural network.

the acceptable levels of voltage were surpassed at several moments of the year. As an example, the results for rural network are shown below.

The range of acceptable voltage for a rural network according to the Uruguayan Regulatory Organism [11] is:

$$0,88\ pu \leq U_{Pto.Conex.} \leq 1,06\ pu$$

Table I shows, for a particular node B15, voltages for a deployment of 50 % and 60 % at the instant of maximum generation. It is observable that a deployment of 60 % would not be admissible and the limit should be at 50 %. This percentage also produces overvoltage but only of 0.1 % in that moment of the year. If, however, a change in the tap of the distribution transformer is allowed, the deployment of microgeneration can reach 80 %.

Regarding the other analysed networks, the limit for the urban network was of 90 % whereas the industrial one presented no problems in relation to overvoltages.

The reason behind this voltage increase is the change in power direction at several moments of the day; while maximum generation occurs near midday, it is not the same for consumption, therefore, the power flows from the load to the substation and the voltage of the load bus increases, as expected from equation (1).

$$\Delta U = U_C - U_{net} \simeq \frac{PR + QX}{U_{Red}} \qquad (1)$$

Where:

$$\begin{cases} P : \text{Active power injected to the grid in the bus BC.} \\ Q : \text{Reactive power injected to the grid in the bus BC.} \\ R : \text{Line's resistance.} \\ X : \text{Line's reactance.} \\ U_{net} : \text{Voltage of external network.} \\ U_C : \text{Voltage of bus BC.} \end{cases}$$

B. Electrical losses

Electrical losses were also calculated in the simulations. The graph in Fig. 2 shows the energy lost in the year of simulation for each level of penetration for the rural network.

From Fig. 2 it is clear that there is an optimal level of penetration, 30 %, for which losses are minimized. From that point losses increase reaching the original value at 50 %. Again, this is due to the non-consumption during

TABLE I
VOLTAGE (P.U.) 19/11 AT 12HRS.

	Voltage (p.u.)			
Node	**Base case** 0 %	**Deployment of** 50 %	**Deployment of** 60 %	**Deployment of** 80 % **(with TAP adjustment)**
BC15	0,9650	1,0610	1,0785	1,0653

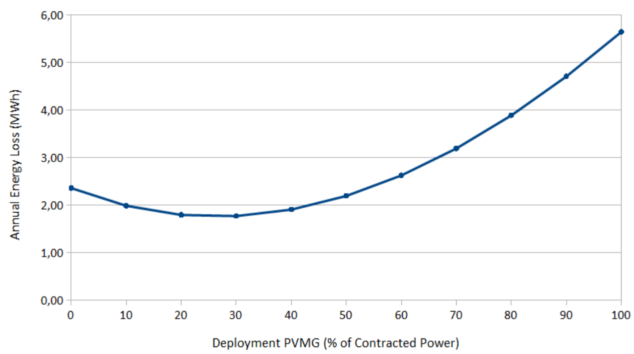

Fig. 2. Evolution of electrical losses by level of penetration of microgeneration.

generation hours, resulting in a surplus of power that flows from the load to the substation. Consequently, a new limit for microgeneration is found, beyond a penetration of 50 % the efficiency of the electrical system begins to deteriorate. It is interesting to mention that the behaviour of the other analysed networks was the same as the one shown in Figure 2.

Regarding the level of loading of lines, it was found that no overload was produced due to a large deployment of microgeneration. Nevertheless, maximum loading increases from 40 %, produced in the hour of higher consumption, till 72 %, when power generation is much greater than consumption, in the urban network; namely, network use does not diminish by the incorporation of microgeneration.

IV. RESULTS OF THE ECONOMIC STUDY

As mentioned before, microgeneration was added in discrete values of 10, 30, 50, 70 and 100 % of contracted power of certain clients. The energy generated in each scenario is shown in Fig. 3. This produces a decrease in the use of thermal generation, as it is shown in Fig. 4, as well as a change in the cost of generation.

The total cost was considered as the composition of two amounts, the cost necessary to be able to generate the energy, the fuel, and the "fixed" cost that is paid to private generators for the energy injected to the grid. Additionally, the flux of costs thanks to the exchange of energy with neighbour countries is also taken into account.

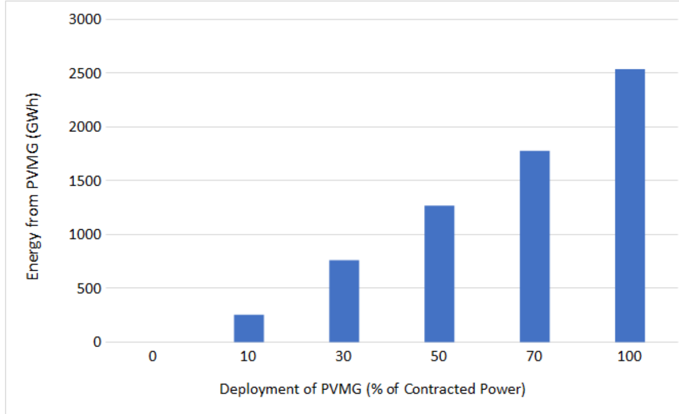

Fig. 3. Energy generated as photovoltaic microgeneration for each scenario.

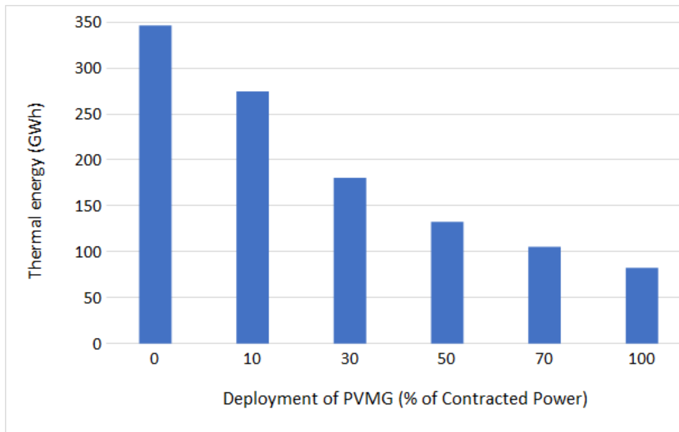

Fig. 4. Thermal generation for each scenario.

Photovoltaic microgeneration does not have a generation cost as the source is solar radiation. On the other hand, it does have a cost for kWh injected to the grid.

In Fig. 5 the evolution of total cost is shown. It is observable that beyond a penetration of 30 % the cost increases with respect to the original case with no microgeneration. However it should be highlighted that, although the total cost increases for a certain amount of generation, it has a decreased until

TABLE II
EVOLUTION OF TOTAL COST FOR DIFFERENT LEVELS OF PENETRATION OF MICROGENERATION.

Deployment (%)	Total cost (MUSD)
0	475,30
10	466,04
30	463,52
50	516,80
70	584,86
100	695,44

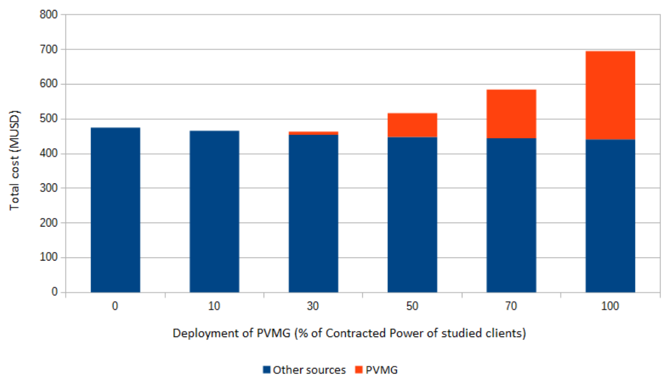

Fig. 5. Evolution of total cost with the increase of photovoltaic microgeneration. It is differentiated by colour the origin of the cost.

30 % and this accounts as a benefit for the system. It must be reminded that only three types of clients were taken into account, therefore this 30 % is a percentage of the sum of the contracted power of the analysed clients, which corresponds to 400 MW approximately. This result could be slightly different if other types of clients with different tariffs were studied.

V. Conclusions

A methodology to determine the potential of microgeneration was established and tested for typical distribution networks in Uruguay. Differently to other approaches, our methodology considers both technical and economical aspects of Microgeneration. First, the impact on low-voltage distribution networks has to be evaluated. A way to do this is to perform quasi-dynamic load flow simulations and calculate voltages at connection points and electrical losses. Furthermore, it is necessary to analyse the change in generation dispatch and its effect in the cost of generation.

In the case of study, the Uruguayan Electrical System, limits to microgeneration were found. From the technical point of view, voltage limits are broken beyond certain level of penetration; this level was 50 % for a rural network. Additionally, it was observable that electrical losses may surpass the original ones deteriorating the efficiency of the network. Regarding the economical aspect, the cost of generation decreases up to a certain level of penetration which, for the Uruguayan case, was of 30 %, which is equivalent to approximately 400 MW, considering the types of clients studied; this number could increase if other types of clients are also included. In conclusion, Uruguay has still great potential to incorporate photovoltaic microgeneration without having a negative impact on the system.

It should be remarked that the aim of this work was to establish a methodology to determine the potential of microgeneration, and the results found are an example of application. Nevertheless, in order to make a thorough analysis all typical networks and all clients with their respective tariffs have to be considered.

Appendix

In the following some of the data used for simulations is presented. In case the demand curves and single-line diagrams are needed, the reader should address the authors.

TABLE III
Contracted power of clients in the urban network.

Client	**CP** (kW)
1	14
2	14
3	34
4	33
5	25
6	20
7	12
8	20
9	12
10	19
11	25
12	30
13	22,8
14	19
15	26,3
23	6,6
24	9,9
25	9,5
16	6,5
17	12
18	6
19	30
20	6,6
21	8,1
22	5

TABLE IV
Contracted power of clients in the rural network.

Client	**CP** (kW)
4	7,4
5	3,7
6	3,3
7	8
8	2,2
9	3,3
10	3,4
11	3,8
12	5,7
13	6,6
14	6,6
15	2,2
16	2,2
17	4,6
18	3,7
1	12
2	4,5
3	5,5

TABLE V

CONTRACTED POWER OF CLIENTS IN THE INDUSTRIAL NETWORK.

Client	**CP** (kW)
1	30
2	50
3	299
4	50

TABLE VI

TRANSFORMERS' DATA.

Network	$\mathbf{S_n}$ (kVA)	$\mathbf{V_{n1}}$ (V)	$\mathbf{V_{n2}}$ (V)	$\mathbf{V_k}$ (%)	$\mathbf{V_r}$ (%)	$\mathbf{V_{fe}}$ (kW)	$\mathbf{i_0}$ (%)
Rural	50	15000	230	4,378	2,194	0,127	2,90
Urban	400	6300	230	3,940	1,186	0,513	0,30
Industrial	630	6300	230	4,040	0,968	0,820	0,29

TABLE VII

CONDUCTORS' DATA.

Type	Section (mm^2)	Material	$\mathbf{I_{adm}}$ (A)	R (Ω/km)	X (Ω/km)	Network
Overhead line	50	Al	150	0,744	0,0931	Rural
	95	Al	230	0,372	0,0891	Urban
Underground	240	Al	420	0,16	0,092	Urban, Industrial
	120	Cu	355	0,19	0,073	Urban, Industrial

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