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Study of technical feasibility and the payback period of the invested capital for the installation of a grid-connected photovoltaic system at the library of the Technological Federal University of Paraná

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Abstract
This article shows the technical feasibility, and the payback period of the capital invested to install a Grid-connected Photovoltaic (PV) system on the rooftop of the library of the Technological Federal University of Parana (UTFPR), Curitiba campus. The rooftop has 897 square meters, and the photovoltaic modules will be used to supply electricity to four consumption scenarios. It is hoped that with the normative resolution 482 of the National Agency of Electric Energy (ANEEL), published in April 2012, the payback period on the initial investment of the PV system is shorter than when there was no such resolution. It is known that, although the resolution represents a breakthrough for inserting the Grid-connected Photovoltaic power generation, it is still not enough to expand this technology. The high tax of the PV equipment and the absence of incentives for this form of generation still prevent large-scale use. In addition, this article also shows the PV systems installed in Florianópolis (LABSOLAR / UFSC) and Curitiba, such as the Green Office (GO), which is situated at the Technological Federal University of Parana.

Keywords: Sustainability; Grid-connected PV system; Law; Political incentive.

1. Introduction

The ANEEL, through BIG (Database of Information of Generation), presents that the total solar power plants in operation is equal to 2.637 kW. However, it is possible that Grid-connected PV systems increase this quality, because of the Resolution 482/2012 from ANEEL. This law is focused on regulate solar power plants in a range of 100 kW to 1 MW, introducing the net metering system [1, 2].
Currently, in some states of Brazil, the implementation costs related to generate electricity through solar panels for the residential consumers are lower than the taxes of the electrical distribution company. This fact predicts a potential growth on Grid-connected Photovoltaic Power Systems [3].
The Grid-connected Photovoltaic Power System in this study is planned to be situated on the rooftop of the library, at UTFPR, Curitiba. An important concept to this paper is the distributed generation, which means that the generator is located near the consumers, reducing the distance between the source of the energy and its final use.

In the electrical system of Brazil, researchers point out that 15 % of the energy generated in huge blocks is lost in transportation. Among advantages and disadvantages of distributed generation, the mainly favorable points could be: the improvement of the efficiency of energy use and the reduction of the loss in transmission grid; the increase of the partial reliability of power supply in the distributed network; it satisfies the partial increase of loads and reduces the investment of electricity generation facilities; and finally, it uses clean energy such as solar, wind and biomass to reduce the emission of wasted gas during electricity generation [4, 5].

2. Solar radiation

The sun may be regarded as a black body that emits radiation at a temperature of 5700 K. The constant is defined as the solar energy from the sun per unit area in a time interval of 1 second. Recent measurements show that this constant is 1367 $W.m^{-2}$ [6].
The radiation received by the earth is the sum of direct and diffuse radiation, conditioned by cloudiness or other weather conditions. This radiation has photons that can be harnessed and converted into electricity, and the energy delivered by them is at least 1 $kW.m^{-2}$ [7].

3. Photovoltaic systems

Photovoltaic systems are responsible for the conversion of sunlight into electricity. These are divided basically in Isolated Photovoltaic System (IPVS) and Grid-connected Photovoltaic System (GCPVS).

3.1 Isolated photovoltaic systems

IPVSs are common where there is no distributed network energy supply. These systems consist of solar modules, charge controller, battery and inverter. The batteries are responsible to feed the loads that can operate in Direct Current (DC) or Alternate Current (AC). This system configuration is noted in Figure 1 [8].

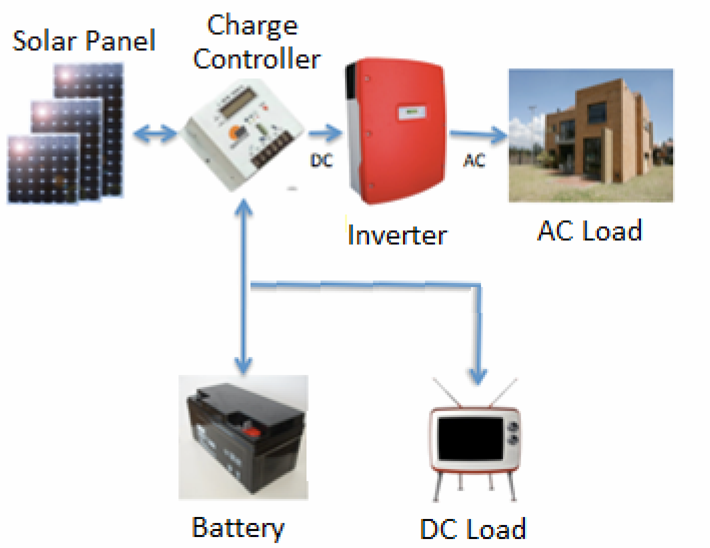

Figure 1. Isolated photovoltaic system configuration. Source: [8]

3.2 Grid-connected photovoltaic systems

The GCPVSs are quite simpler than the SFIs, because they consist of the solar modules, compounding a solar panel and the inverter. This system operates generating electrical energy in parallel to the distributed network. There are two ways to cause an insufficiency on the power generated by the solar panel: the increase of the loads or the low levels of solar radiation. This kind of system has the electric network providing a backup in case of insufficiency on the power generated.
On the other hand, when there is more power generated than the loads consumption, this power is injected in the grid. This system is used in urban areas, since there is availability of electricity supply to consumers in times of low productivity and it is also possible to convert the amount of energy that exceed the loads consumption into a credit to be used by the consumer on his next energy bill, in

accordance to Resolution 482/2012 [1]. Another feature of this system is that if there is a fault in the network, the inverter automatically shuts down the system. Thus, the phenomenon of "islanding" is avoided, giving greater security to network operators by preventing injection of energy from this source [9]. This system configuration is noted in Figure 2.

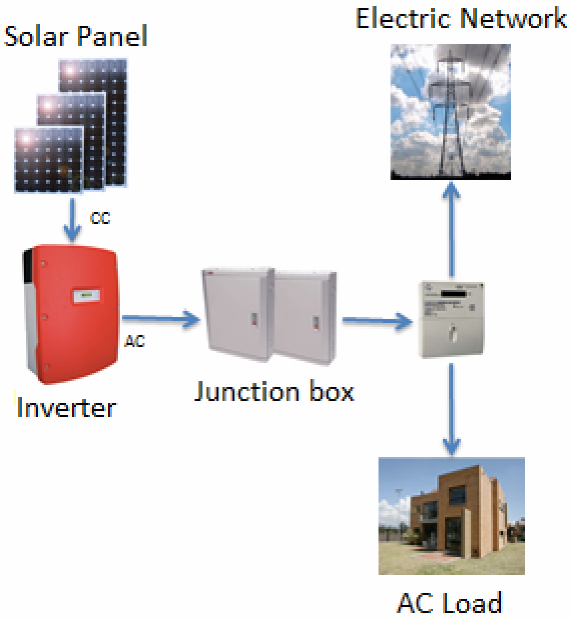

Figure 2. Grid-connected photovoltaic system configuration. Source: [8]

4. Photovoltaic systems in Brazil

4.1 System of Federal University of Santa Catarina

Situated at the Solar Energy Laboratory – LABSOLAR, at the UFSC (Federal University of Santa Catarina), there is the first Grid-connected Photovoltaic System of Brazil, with a total implanted power of 2 kW, provided by 65 solar modules with the amorphous silicon cells (a-Si), 52 being opaque and semi-transparent 13 [10]. In the Figure 3 the system is shown [11]. The system occupies an area of 40,8 m² and previously was divided in four circuits with an Wurth 650W inverter. After November 2008, the inverters were replaced by a high efficient one, with 2500 W.

Figure 3. Solar energy laboratory – LABSOLAR. Source: [11]

4.2 System of the green office of UTFPR

The Green Office is a project that aims to show the use of solar energy in a sustainable building, situated at the UTFPR. The whole system is divided into the two configurations explained, the Grid-connected Photovoltaic System and the Isolated Photovoltaic System. The first one consists of ten modules of 210 W, which was built with polycrystalline silicon cells, and a 2000 W inverter [12, 13]. In Figure 4 the system is shown.

Figure 5 shows the general single line diagram of this installation. The electrical panel of the Green Office is called QFL-V-05-TR and its energy consumption is monitored by the Power meter 2.

Figure 4. Green office photovoltaic system. Source: [13]

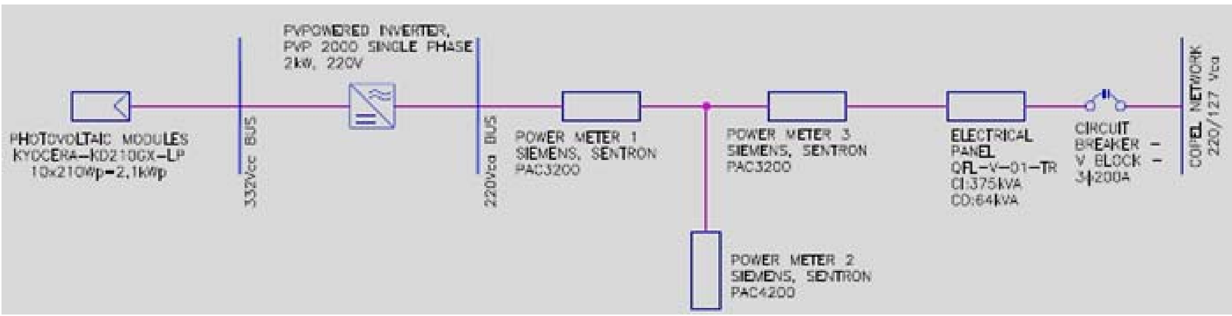

Figure 5. General single line diagram of green office. Source: [13]

This system generated 5,95 MWh from December 14, 2011 to June 18, 2014.

The IPVS has a total implanted power of 870 Wp and is composed of two arrays, one consists of two modules, totalizing a power of 174 Wp, and the other consists of eight modules, totalizing a power of 696 Wp. Figure 6 presents these two arrays.

5. Design of the photovoltaic system

5.1 Scenarios for the photovoltaic power generation

To design the GCPVS, four different scenarios of load consumption were considered, as shown in Table 1. The load description, which was the base for the calculations, is shown in “Appendix”.

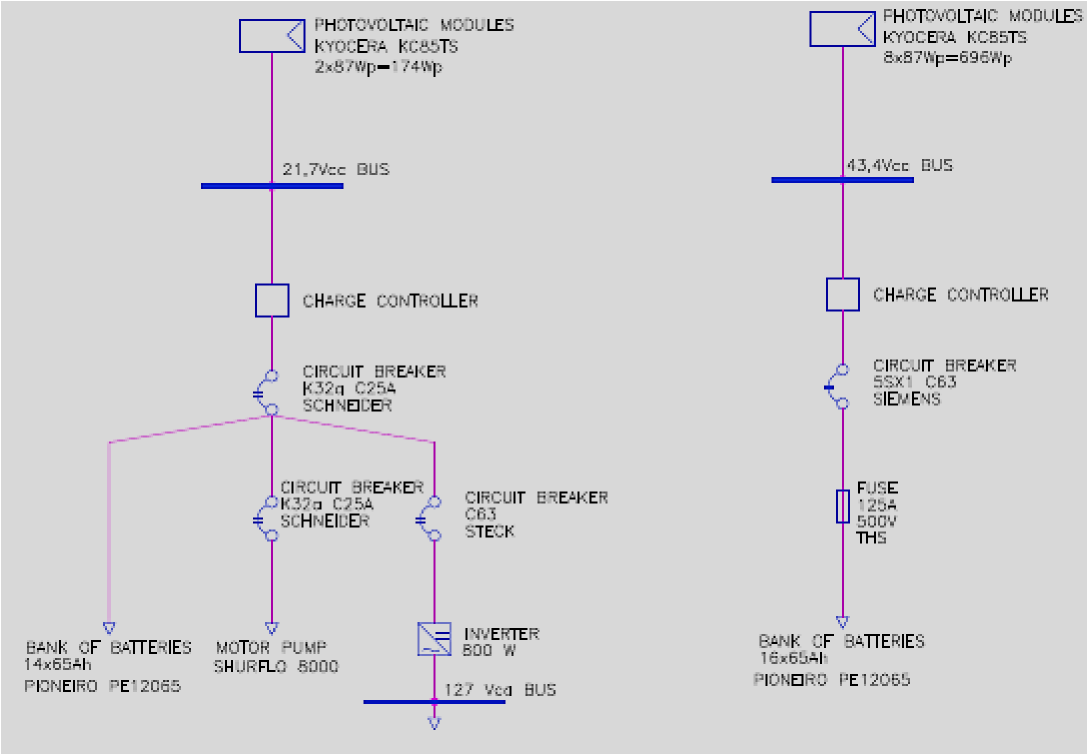

Figure 6. Single line diagram of SFI which consists of two arrays. Source: [13]

Table 1. Scenarios of energy consumption. Source: The authors

Scenario	Load descriptions	Diary consumption (Mon-Fri) (kWh)[2]	Diary consumption (Sat) (kWh)[3]	Photovoltaic power (kWp)[4]
1	Lighting and TUGs[1] at the 1st floor	142,98	67,9	46,6
2	Total loads at the 2nd floor and electrical sockets for the BWC at the 1st floor	96,47	45,8	31,4
3	Electrical sockets for the computers at the 2nd floor	37,44	17,8	12,2
4	TUGs and electrical sockets for the BWC at the 1st floor	21,35	10,1	7,0

[1]: TUGs: Electrical sockets for general use
[2]: The diary consumption was calculated in order to design the photovoltaic power. The period considered to have solar radiation was from 8 to 18 h, which occurs from Mondays to Fridays.
[3]: In this case the period considered was from 8 to 12:45, because on Saturdays it is when the library is working.
[4]: The formula is given by the Equation 1, considering the diary consumption from Monday to Friday, which is the critical case.

$$P_{FV} = \frac{EG}{H_{TOT} PR} \tag{1}$$

where P_{FV} is the photovoltaic power system installed (Wp); E is the load consumption (Wh/day); G is the irradiance under Standard Test Conditions (STC) (1.000 W/m²); H_{TOT} is the solar radiation incident on the surface of the photovoltaic modules (Wh/m².dia); PR is the performance ratio, equal to 0,75.
For this paper, the load consumption was considered to be constant during the days. This point is justified because there is no energy metering specific for the library, so the real load profile is not predictable.

5.2 Requirements

The following requirements were considered:

- Photovoltaic modules inclination and orientation are optimum, which means that the inclination is equal to the latitude of Curitiba and the orientation is to the geographic north [14]. Inclination: -25,43° [15];
- From the database SWERA (Solar and Wind Energy Resources Assessment), which provides the radiation in the horizontal plane and in the tilted plane (the tilted plane has an angle equal to the local latitude), it was possible to obtain the monthly average daily irradiation that is obtained by the photovoltaic module surface. The geographic coordinates of Curitiba, -25,43° S and -49,27° W, were the input values in the database SWERA. From this, were calculated the annual average daily irradiation in Curitiba, which resulted in 5,001 kWh/m². According to Montenegro [16], 80% of the result is used, although Fusano [17] has found a difference of 5,5% between annual average daily irradiation obtained at the weather station INMET and database SWERA. To conclude, this paper considered 5,5% of the annual average daily irradiation in Curitiba, which is equal to 4,726 kWh/m²;
- The global solar irradiance is equal to 1000 W/m², assuming STC;
- The performance ratio is equal to 0,75;
- The lifetime of the modules is at least 25 years and can reach up to 35 years [18].

The Table 2 presents the photovoltaic power system designed through the requirements above and the diary consumptions at the Table 1. The generated energy was calculated by using Equation 1.

Table 2. Photovoltaic power system designed. Source: The authors

Scenarios	1	2	3	4
Photovoltaic power (kWp)	46,6	31,4	12,2	7,0
Generated energy (kWh)	143,0	96,5	37,4	21,4

5.3 Photovoltaic power system costs

In the Table 3 is presented the investment cost for photovoltaic power systems, according to EPE [19]. Table 4 presents the costs applied to the grid-connected photovoltaic power systems of the library.

Table 3. Photovoltaic power systems investment costs (R$/Wp). Source: [19]

Power	Modules	Inverters	Instalation and services	Total
Residencial (4-6kWp)	4,88	1,25	1,53	7,66
Residencial (8-10kWp)	4,42	1,09	1,38	6,89
Comercial (100kWp)	3,81	0,92	1,18	5,91
Industrial (≥1.000kWp)	3,50	0,66	1,04	5,20

Table 4. Photovoltaic power systems total costs. Source: The authors

Scenario	Item	Power (Wp)	Unitary cost (R$/Wp)	Partial cost	Total cost (C_T)
1	Module	46555	3,81	R$177.374,5	R$ 275.139,97
	Inverter	46555	0,92	R$42.830,59	
	Instalation & services	46555	1,18	R$54.934,88	
2	Module	31409	3,81	R$119.669,67	R$ 185.629,32
	Inverter	31409	0,92	R$ 28.896,61	
	Instalation & services	31409	1,18	R$ 37.063,05	
3	Module	12190	3,81	R$ 46.445,71	R$ 72.045,71
	Inverter	12190	0,92	R$ 11.215,24	
	Instalation & services	12190	1,18	R$ 14.384,76	
4	Module	6952	4,42	R$ 30.725,93	R$ 47.896,30
	Inverter	6952	1,09	R$ 7.577,21	
	Instalation & services	6952	1,38	R$ 9.593,16	

5.4 Study of the payback period of the invested capital

The study of the payback period of the invested capital was based on the following requirements.

- It was calculated the time required to recover the capital invested in the project implementation;
- the energy tax price is included on the category horossazonal green, A4 group whose supply voltage is between 2.3 and 25 kV;
- the Normative Resolution n° 482 of the National Electric Energy Agency (ANEEL) proposes the insertion operation of microgeneration, which reaches up to 100 kW of power distribution systems. According to this resolution, the generated active power that exceeds the consumption creates an energy credit to be used primarily at the same time of generation. Therefore, this credit is valid primarily for the hours of sunshine, which are included in the off-peak period, which is when there is photovoltaic generation (off-peak period is between 21:01 and 17:59). These credits are valid for up to 3 years.
- the calculations related to the payback period of the invested capital depart weekly analysis, which is divided as follows: Monday to Friday, when all the energy generated by the system is absorbed by the loads, resulting in energy savings that can be treated in financial terms; Saturday, when part of the energy generated is absorbed by the loads, as is valid from Monday to Friday, and the rest of the energy flows of the dependencies UTFPR or is injected into the network so that it can also be assessed financial return; Sundays, when all energy generated is injected into the network, or into the UTFPR electrical installation that is not located in the library. The behavior of the loads in practice, present variations throughout the day, but were not considered in this paper, due to not having a study of the behavior of the library loads. In Table 5 the energy taxes from the *Companhia Paranaense de Energia* (COPEL) are shown [20].

Table 5. COPEL energy taxes. Source: [20]

Consumption (R$/kWh)		Demand (R$/kWh)		
Peak	Off-peak	Peak	Off-peak	Exceeding
R$ 1,00493	R$ 0,22597	R$ 8,25000	R$ 8,25000	R$ 16,50000

Firstly, the calculations considered an annual decrease of productivity equal to 0,5%. [16]. Secondly, three conditions were pointed out.

- Condition 1: The university must pay ICMS, PIS and COFINS taxes, which represents 35,56% of the energy injected in the electric network [16].
- Condition 2: The university must pay ICMS, PIS and COFINS taxes just for the consumption.
- Condition 3: The university must pay ICMS, PIS and COFINS taxes just for the consumption and the exceeding energy that is injected in the electric network is sold for the double price of the energy bought from the network.

5.4.1 Results of the payback period of the invested capital for the three conditions

The payback period of the invested capital was calculated from the Equation 2. The annual financial returns were summed until the result was the amount of capital invested in the project.

$$\sum_{i}^{n} RFA_{Ti} \tag{2}$$

where i is the year; RFA_T the annual financial return of the year i. Logically, the weekly financial return was calculated, as shown in the Equations 3, 4 and 5.

$$RFS_{C1} = E_{p_1} T_{C_{FP}} 5 + \left(E_{P_2} T_{C_{FP}}\right) + \left(E_{i_1} + E_{i_2}\right) T_{C_{FP}} 0.64 \tag{3}$$

$$RFS_{C2} = E_{p_1} T_{C_{FP}} 5 + \left(E_{P_2} T_{C_{FP}}\right) + \left(E_{i_1} + E_{i_2}\right) T_{C_{FP}} \tag{4}$$

$$RFS_{C3} = E_{p_1} T_{C_{FP}} 5 + \left(E_{P_2} T_{C_{FP}}\right) + \left(E_{i_1} + E_{i_2}\right) T_{C_{FP}} 2 \quad (5)$$

where RFS_{C1} is the weekly financial return to the condition 1 (R$); RFS_{C2} is the weekly financial return to the condition 2 (R$); RFS_{C3} is the weekly financial return to the condition 3 (R$); E_{P1} is the diary saved energy, which means the energy absorbed from the photovoltaic power system, without demanding the network, from Monday to Friday (kWh); E_{P2} is the diary saved energy during the Saturday (kWh); E_{i1} is the diary injected energy, which means the amount of energy generated that exceeds the loads consumption, during the Saturday (kWh); E_{i2} is the diary injected energy, during the Sunday (kWh); Tc_{FP} is the energy tax for the period of photovoltaic generation (R$/kWh).
The equations 6, 7 and 8 show the calculation of the monthly financial return, while the Equations 9, 10 and 11 shows the calculation of the annual financial return.

$$RFM_{C1} = RFS_{C1} 4 \quad (6)$$

$$RFM_{C2} = RFS_{C2} 4 \quad (7)$$

$$RFM_{C3} = RFS_{C3} 4 \quad (8)$$

$$RFA_{C1} = RFM_{C1} 12 \quad (9)$$

$$RFA_{C2} = RFM_{C2} 12 \quad (10)$$

$$RFA_{C3} = RFM_{C3} 12 \quad (11)$$

where RFM_{C1} is the monthly financial return to the condition 1; RFM_{C2} is the monthly financial return to the condition 2; RFM_{C3} is the monthly financial return to the condition 3; RFA_{C1} is the annual financial return to the condition 1; RFA_{C2} is the annual financial return to the condition 2; RFA_{C3} is the annual financial return to the condition 3.
The annual financial returns were summed until the result was the amount of capital invested in the project, as shown in the Tables 6, 7, 8 and 9. Table 10 sum up the payback period of the invested capital for the three conditions.

Table 6. Payback period of the invested capital: scenario 1 of energy consumption. Source: The authors

Year	Annual financial return accumulated (RFA_{C1}) (R$)	Annual financial return accumulated (RFA_{C2}) (R$)	Annual financial return accumulated (RFA_{C3}) (R$)
1	10.004,62	10.856,04	13.221,10
2	19.960,53	21.657,80	26.372,43
3	29.868,00	32.405,55	39.454,31
4	39.727,25	43.099,56	52.467,10
5	49.538,53	53.740,10	65.411,14
22			275.268,05
28		284.313,18	
30	279.911,24		

6. Conclusions

Since there is no compensation, like deductions in income tax and fiscal incentives, regarding the installed photovoltaic power, as well as because of the same unitary installation costs for this power range, the payback period of the invested capital was the same for the scenarios 1, 2 and 3. On the other hand, for a smaller installed photovoltaic power system (7 kW), the prices are higher, so there is an increase in the payback period of the invested capital for scenario 4.
The payback period of the invested capital for the implementation of the library grid-connected photovoltaic power system in UTFPR is smaller than the lifetime of the modules, for scenarios 1, 2, 3

and 4 in the three conditions studied [18]. It is important to clarify that in this article were suggested three conditions for achieving results, but the number of these conditions could increase as more systems will have been installed and the rates that could be charged in an interconnection to the network of Copel will have been set. The expectative is that the rates that will be charged in GCPVSs will become clearer, considering that there will be more systems in operation in Parana.

Table 7. Payback period of the invested capital: scenario 2 of energy consumption. Source: The authors

Year	Annual financial return accumulated (RFA_{C1}) (R$)	Annual financial return accumulated (RFA_{C2}) (R$)	Annual financial return accumulated (RFA_{C3}) (R$)
1	6.749,84	7.324,27	8.919,91
2	13.466,82	14.611,92	17.792,74
3	20.151,11	21.863,13	26.618,72
4	26.802,88	29.078,08	35.398,09
5	33.422,28	36.256,96	44.131,07
22			185.715,67
28		185.421,07	
30	188.848,40		

Table 8. Payback period of the invested capital: scenario 3 of energy consumption. Source: The authors

Year	Annual financial return accumulated (RFA_{C1}) (R$)	Annual financial return accumulated (RFA_{C2}) (R$)	Annual financial return accumulated (RFA_{C3}) (R$)
1	2.619,72	2.842,67	3.461,96
2	5.226,69	5.671,12	6.905,65
3	7.820,97	8.485,43	10.331,15
4	10.402,63	11.285,67	13.738,56
5	12.971,72	14.071,91	17.127,98
22			72.079,22
28		74.447,73	
30	73.295,09		

Table 9. Payback period of the invested capital: scenario 4 of energy consumption. Source: The authors

Year	Annual financial return accumulated (RFA_{C1}) (R$)	Annual financial return accumulated (RFA_{C2}) (R$)	Annual financial return accumulated (RFA_{C3}) (R$)
1	1.493,88	1.621,02	1.974,17
2	2.980,50	3.233,93	3.937,92
3	4.459,87	4.838,78	5.891,30
4	5.932,05	6.435,60	7.834,36
5	7.397,07	8.024,44	9.767,15
26			48.073,28
32		48.046,38	
35	48.188,18		

Table 10. Payback period of the invested capital to the conditions 1, 2 and 3. Source: The authors

Scenario	Time to the condition 1	Time to the condition 2	Time to the condition 3
1	29 years and 6 months	27 years and 1 month	22 years
2	29 years and 6 months	27 years and 1 month	22 years
3	29 years and 6 months	27 years and 1 month	22 years
4	34 years and 10 months	31 years and 11 months	25 years and 11 months

It may be mentioned, too, that the legislation is incomplete, although it represents a breakthrough with the introduction of net metering concept that before its publication, in April 2012, was unknown in

Brazil. The proposed on the condition 3 of this study is the possibility of commercialization between the consumer and the electric network, through the sale of the exceeding energy that is injected in the network. This practice is called Feed-in tariff and represented huge increases on the installed photovoltaic power in countries like Germany, which is a country that invests extensively in solar energy. In this case, the consumer becomes also a minigenerator of energy, and that energy generated in case of surplus is sold to the dealership for a premium rate 2,5 to 3 times the normal rate. This variation is a function of the location of the installation and the power installed [21]. This practice is already current in Japan as well, where a new Feed-in scheme started on July 2012 and brought an increase of 33% on the installed photovoltaic power comparing that year to the previous one. This new Feed-in scheme is aimed to non-residential segments, like large scale photovoltaic projects, in the industrial and commercial sectors. Researches pointed out that the payback period for a 100 kW solar photovoltaic plant in Japan is 8,05 years, which is quite less in comparison to the 14,65 years obtained in Germany [22].

Brazilian legislation related to the implementation of solar photovoltaic energy as a form of distributed generation is very different when compared to Japan and Germany for example. According to the law N. 10848/2004 and Decree N. 5163/2004, it is not allowed to sale the exceeding energy to the electric network. So, it represents a barrier for the economic feasibility of grid-connected photovoltaic systems. However, there are other public policies that might encourage the expansion of grid-connected photovoltaic systems, such as financing of equipment, deductions in income tax and fiscal incentives [23].

It is also important to mention that this research is a simplified economic analysis, although its results are consistent with the literatures that still conclude the economic unfeasibility on grid-connected photovoltaic systems. However, this and many other researches are limited because it does not take into account the negative externality costs that occur for other decentralized energy sources, like fossil fuel. This source pollutes the air and contribute to the increase on greenhouse gases emission, so it has a societal cost, because affects everyone's life. The evaluation of the impacts of externalities should be developed and it would be an important and favorable step for decision making on renewable energies [24].

To conclude, the power tariff in the tariff structure horossazonal green of COPEL, which is what fits UTFPR, is still cheap so the payback times become longer when compared to others Brazilian states [16]. If the rate increases will be possible to obtain a shorter payback period on the invested capital. It is worth mentioning that this study is not considering a possible reduction in demand due to the installation of GCPVS, which would imply savings in electricity bills, reducing the time of return on invested capital. It is a suggestion for future work, to make a study of the possible demand reduction in UTFPR with the installation of a GCPVS and to perform such a study, it is necessary to access the mass memory of the Power Metering in operation at the university.

Appendix

The loads and its descriptions are shown in reference to the electrical panels QFL-L-01-PR, QFL-L-01-SG and QFL-L-01-TC, which are installed on the first, second and third floor, respectively, at the library.

QFL-L-01-PR					
Load descriptions	**Installed power (W)**	**Demand factor**	**Demanded power (W)**	**Time of usage (h)**	**Diary energy consumed in average (kWh)**
Lighting	15744	0,8	12595,2	13,75	173,18
Ventilation	3876	1	3876	13,75	53,30
TUGs	17030	0,1	1703	13,75	23,42
Electrical sockets for computers	12480	0,9	11232	13,75	154,44
Electrical sockets for bathroom	4320	0,1	432	13,75	5,94
QFL-L-01-SG					
Load descriptions	**Installed power (W)**	**Demand factor**	**Demanded power (W)**	**Time of usage (h)**	**Diary energy consumed in average (kWh)**
Lighting	4912	0,8	3929,6	13,75	54,03
Ventilation	1020	1	1020	13,75	14,03
TUGs	3770	0,1	377	13,75	5,18
Electrical sockets for computers	4160	0,9	3744	13,75	51,48
Electrical sockets for bathroom	1440	0,1	144	13,75	1,98
QFL-L-01-TC					
Load descriptions	**Installed power (W)**	**Demand factor**	**Demanded power (W)**	**Time of usage (h)**	**Diary energy consumed in average (kWh)**
Lighting	5040	0,8	4032	13,75	55,44
Ventilation	1224	1	1224	13,75	16,83
TUGs	4030	0,1	403	13,75	5,54
Electrical sockets for computers	4680	0,9	4212	13,75	57,92
Electrical sockets for bathroom	960	0,1	96	13,75	1,32

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