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PROPOSAL OF A PROFITABLE RENEWABLE ENERGY PROJECT POWERED WITH SOLAR POWER FOR A MIDDLE-CLASS HOUSEHOLD IN THE CITY OF BOGOTÁ, COLOMBIA

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Abstract

This investigation aims to show the feasibility of installing a complete energetic system composed of solar panels in the city of Bogotá, Colombia in a four-member middle-class household and explore the economic advantages in terms of profitability that could be achieved in the long term after its incorporation. Aspects such as energy consumption habits, type of electronic devices in the house, family activities, solar radiation and implementation expenses are going to be considered to make the projection as accurate as possible. These types of projects become feasible because of incentives as Law 1715 of 2014 (MinEnergia 2014) in which households are given tax exemptions for renewable energy investments.

Key words: Renewable energy sources, solar power system, profitability, energy consumption, economic payback.

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Summary of rooftop solar analysis

Location: Bogotá, Colombia **Date of analysis**: Nov/2021

Recommendation*: install 3 solar panels (4.89 m^2), for a net present value of 4.729 million COP (equivalent to 1073 euros), with a payback of 6 years.*

Main economic results:

Financing	NPV (COP '000)	Payback (years)	IRR (%/year)	LCOE (COP/kWh)
75% debt	4.729	6	5.21%	309.66

Additional results:

A system of 3 panels requires an initial investment of over 5 million COP but provides an NPV of over 4 million pesos in 6 years along with an increase in the trust of the electrical system in case of shortages as well as a positive environmental impact.

Main inputs and assumptions:

Household and Economics					
Electricity Consumption	2,134.6	kWh/year	Inflation	2%	per year
Electricity price – buy	504.78	COP/kWh	Bank loan interest rate	15%	per year
Electricity price – sell	229.41	COP/kWh	Bank loan maturity	5	years
			Equity cost of capital	0.17%	per year

PV panels chosen					
Peak power	260	W/panel	System losses	13.5%	of output
Panel area	1.63	m^2/panel	Degradation with age	0.5%	Per year
Useful life	25	Years	Maintenance costs	30,000	COP/year per panel
			Total cost of optimal installation size	5,349,092	COP

Government subsidies:

The government makes an exemption of tax payment to the necessary elements to install a domestic photovoltaic solution within which are the panels and microinverters. There is also a tax exemption to the purchase and sale of electricity since public services are not under the tax regime.

INTRODUCTION

The implementation of innovative renewable energy sources and the multiple programs that local governments are providing for those means are incentivizing many households to change their energy providing systems towards more ecological and sustainable approaches. A good example of this situation would be Colombia, specifically the city of Bogotá, where the government has been creating laws such as the Law 1715 of 2014 (MinEnergia 2014) which aims to promote commercialization and autonomy of energy production by households without reducing energy-saving comfort, this means that homes could be able to produce their own energy, consume and further sell it to the local energy network. This type of incentives is useful in the way that it allows people to track, monitor and control their connected devices and thus be able to improve multiple aspects such as technical, economic, social, and environmental.

The present thesis work project aims to show the feasibility of installing a complete energetic system composed of solar panels in the city of Bogotá in a middle-class household composed by four members (two adults and two kids) and explore the economic advantages in terms of profitability that could be achieved in the long term by incorporating a renewable energy source following the financial management guidelines given by (González, Guzmán y Trujillo 2020). This investigation considers multiple financial indicators like the IRR, NPV and a thirty-year projection that will give a broader overview of the profitability that a project of this matter may provide to all the stakeholders involved. Aspects such as energy consumption habits, type of electronic devices in the house, family activities and solar radiation are going to be considered to make the projection as accurate as possible.

The investigation process consists of literature research in which the energy consumption habits of a household are modelled compiling trends of multiple houses with similar characteristics as the one desired for this specific study. Regarding the estimation of radiation levels of the city, the daily radiation per day of the year forecasted by consulting multiple authorized measurement sources and generating an accurate average consistent with the seasonality of the region. As for the costs of implementation, market research that implies multiple providers of solar energy power solutions is addressed in which the one that offers the best solution in the market as for the product quality, installation, maintenance is considered. It is important to highlight that the consumption habits of a household are subject to change specially when considering a long-term forecast because of changes in the season of the year or technological innovations that could reach the market during that same period.

1. Bogota´s solar power energy background

a. General overview

Bogotá city is the capital of Colombia, located in the Eastern Mountain Range of the Andes at 2600 meters above the sea level and counts with a 340 square kilometer spread. By 2021 its population has been stablished at 7.2 million and a density of 210 pp/ha (P Nair 2005).

Law 142 of 1994 stablished those public services paid by households must be proportional to the income of the family, and thus the cities were sectorized depending on income. The sectors go from 1 to 6, in which the lowest ones are the families with the lowest income and the higher ones are the ones with highest income. The purpose of this sectorization is for families with higher incomes to pay for families who cannot afford that (Méndez 2019). For this investigation's purpose we are considering a middle-class family which will be living in house in category 4.

Colombia is a country that counts with abundant natural resources -specially water- which is why the main source of electricity comes from hydroelectric generation followed by gas and coal. Figure 1 shows Colombian electricity production breakdown as for 2020.

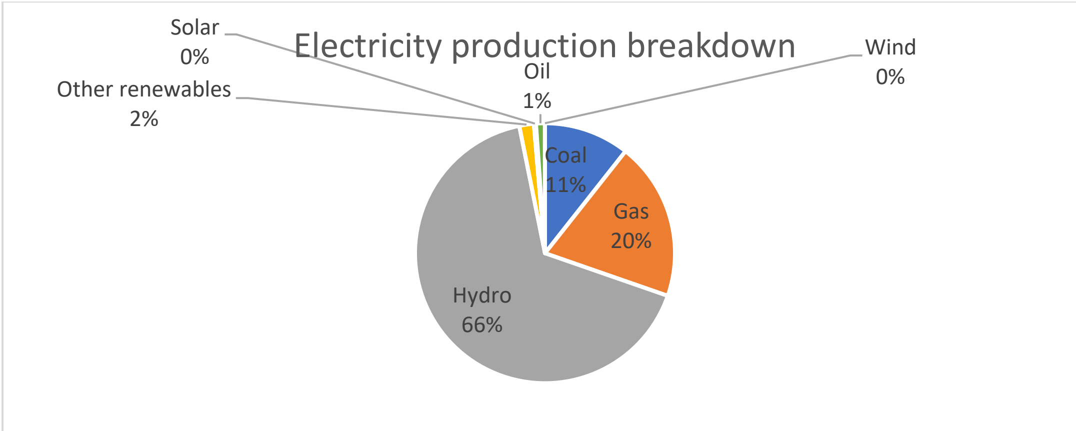

Figure 1. Electricity production breakdown. Source: Author based in (Ritchie y Roser 2019)

Figure 2 shows the growth of energy consumption trends from 1965 until 2019.

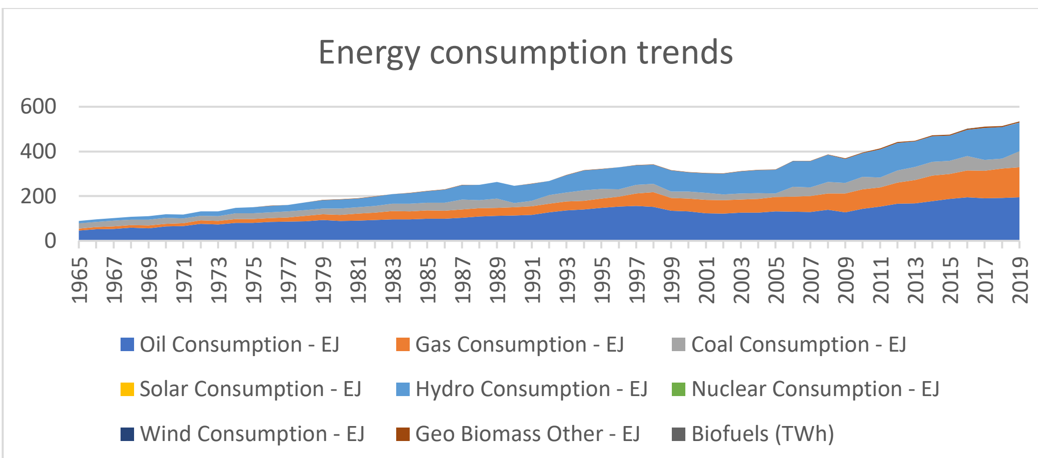

Figure 2. Energy Consumption trends. Source: Source: Author based in *(Ritchie y Roser 2019)*

b. Government regulations

Colombian government is no stranger about the elevated greenhouse gas emissions caused by the growth of electricity consumption and the lack of enough renewable energy systems. However, Law 1715 of 2014 (Unconventional Renewable Energies Law) aims to incentivize the development and use of renewable energy sources. Among the benefits offered by this law are the injection of autonomously created energy into the national grid and receiving an economic benefit in return.

The beneficiaries are called "cogenerators", who in turn are given a tax exemption on machinery, equipment and labor expenses as well as a maximum of 50% deductible tax for up to 5 years in the case of industrial manufacturers and no taxation in the purchase of photovoltaic systems except for batteries for regular households (Camara de comercio Cali 2016).

Colombia, being considered as an emerging market, counts with multiple limitations at the time of implementing projects of this nature among which can be found a wrong incentive program, higher costs due to lack of infrastructure or transactional costs, regulation made for conventional energy generation, etc. Specifically talking about photovoltaic system barriers there is the lack of energetic policies or smart networks to track operations as well as a lack of normativity that stablishes the technical requirements for a specific project and a reduced workforce trained to do installations and maintenance in areas of difficult access (MME 2015).

c. Radiation advantages because of localization Colombia's geographic location

The geographic location of Colombia is beneficial for photovoltaic energy production projects. Since it is in the equatorial zone, it has an average of 12 hours of solar radiation per day throughout the 365 days of the year, of which generally 4 can be used to the maximum by solar panels arranged to generate electricity depending on the area in which they are located. The figure below shows a summary of the radiation levels by area, where the northern area is the one with the highest photovoltaic potential of the order of 6.0 Kwh / m2, which is comparable with areas such as Arizona or New Mexico in the States (Forero, Hernández, et al 2019).

Figure 3. Radiation per zone in Colombia. Source: (Global solar atlas s.f.)

However, the central area of the country, known as the Andean region and where Bogotá is located, has radiation levels of around 4.5 kWh / m2, which is also beneficial for increasing the photovoltaic capacity of the country in general. The Figure 4 below shows the growth of the installed capacity in the country from 2015 to 2020 in MW.

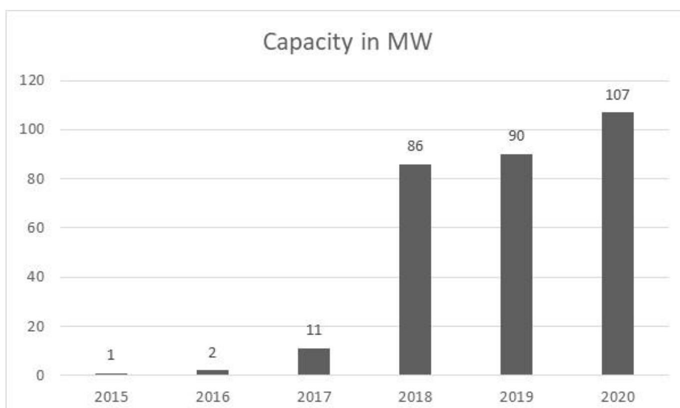

Figure 4. Photovoltaic capacity in Colombia. Source: Author based in (Statista 2021).

This evident increase shows evidence the good position in which Colombia is situated energy wise.

d. Historic radiation measurements in the area

The information about the historic radiation measurements in the city of Bogotá were gathered from the European Geographical Information System. The information was extracted hourly and summarized in the Figure 5:

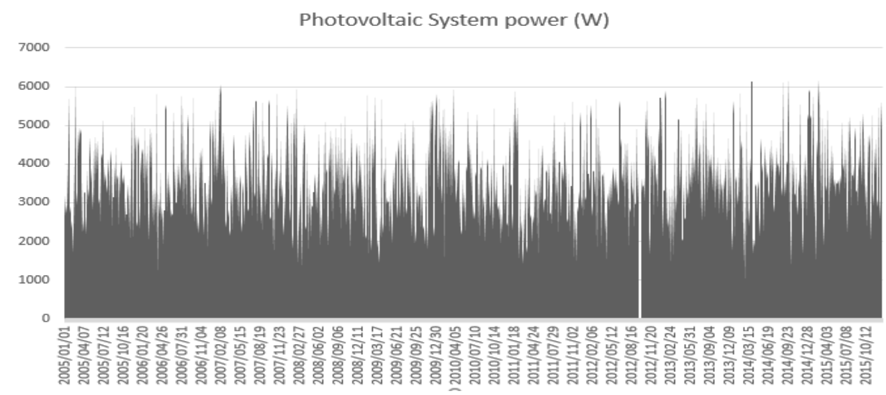

Figure 5. Photovoltaic System Power in Bogotá. Source: Authors based in (European Commission 2020)

As can be observed in the graph, it shows a stable trend during the selected time period indicating that there are no seasonal changes in the radiation. Historically, the average power is 3,500W/m2 and a standard deviation of 1,046W. This makes sense if the geographical location of the city is considered due to the absence of seasons during the whole year.

e. Solar panel market overview

There are three systems for residential solar power implementations: isolated, hybrid or connected to the network. A shared characteristic among the three systems is that all of them must have a power control unit and a storage unit preferably (Camara 2011).

I. Isolated systems

These systems only include solar panels, inverters, controllers, and batteries. They are commonly used as energy source for conventional domestic devices; however, they are not the most viable economically because of their elevated costs but are useful in terms of reliability and emergency. The payback period of these systems is around 20 years (Camara 2011).

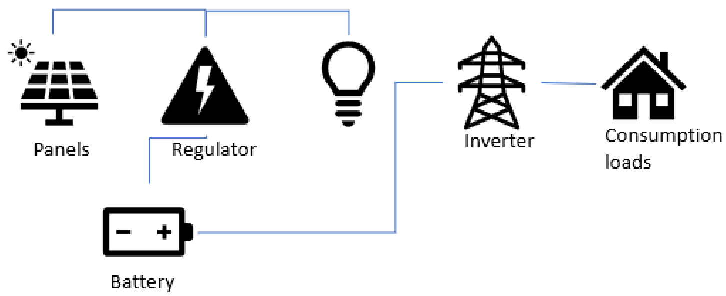

Figure 6. Isolated system components. Source: Author based in (Sun Supply 2020)

II. Hybrid systems

These systems work as electricity source for bigger amounts of users. Usually include wind turbines, diesel generators, solar panels, etc. which makes the energy supply more optimal. The energy generated by all the different sources is stored in batteries until demanded by the final users (Camara 2011)

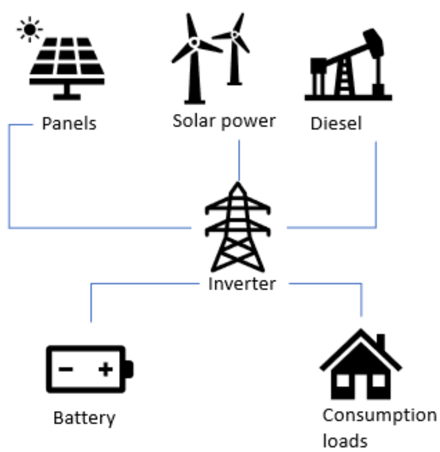

Figure 7. Hybrid system components. Source: Author based in (Sun Supply 2020)

III. Systems connected to the grid

These systems do not use energy storage systems since all the generation is provided directly to the grid. If the system is allowed to generate enough energy to supply the demand, then the demand will all be supplied by the photovoltaic system, otherwise the demand will be supplied by the electric network (Camara 2011). Also, if the photovoltaic system is able to produce more energy than the demanded, then it will inject it to the network and generate economic profit out of its operation. This investigation is going to focus on this type of system.

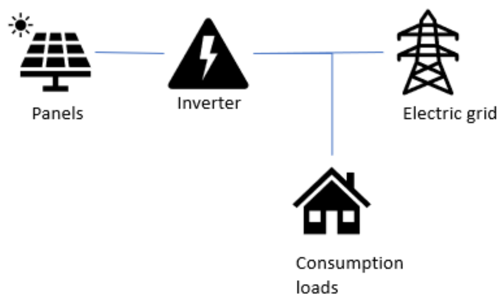

Figure 8. Components of a system connected to the grid. Source: made by Author based in (Sun Supply 2020)

The panel generates in direct current, which is converted in alternating current by the inverter to supply domestic demand. It is important to recall that the generator will only work during the day, so the electricity demand during nighttime will be fully supplied by the grid.

2. Characterization of the consumption habits of a middle-class family located in Bogotá, Colombia

a. Generalities of domestic electrical system

Throughout the Colombian territory, domestic electrical energy is 110 volts of alternating current at 60 hertz (110V AC, 60Hz). In industrial facilities or specific uses it is 220 volts of alternating current at 60 hertz (220V AC, 60Hz) (Consulado de Colombia 2019). The monthly consumption of a Colombian household is around 157 kWh per month which is low when comparing to other

South American countries given the lack of electric structure in Colombia and the usage of gas as an alternate energy resource in devices such as the stove or water heater for instance (UPME 2019).

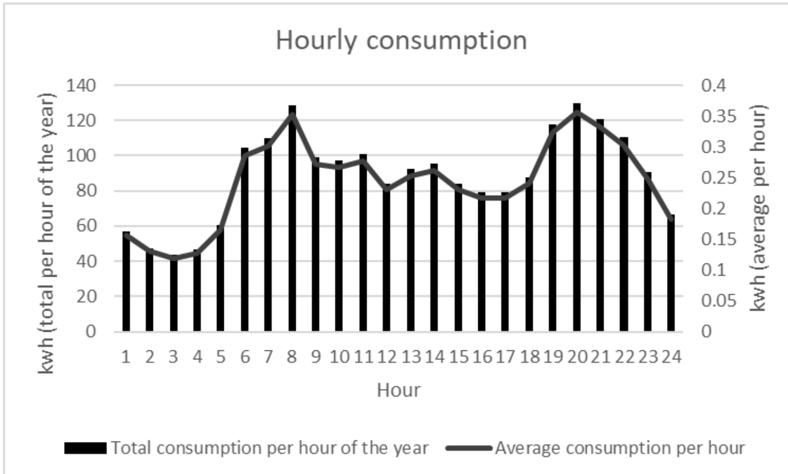

Figure 9. Average consumption per home per hour of the day. Source: Author based on (Hernandez, 2017)

Figure 9 shows the change in the electricity consumption for a middle-class family in the city of Bogotá. This data was modified considering the 1.2% increase in the demand caused by the pandemic during 2020. (UPME 2020). The peak hours coincide with the early day starting times (around 6am and 9 am) and early nights (19 and 22). The behavior that this graph shows matches the general demand curve in Colombia and supports the politic practices encouraged by the Colombian Government such as Law 1715 which promotes the flattening of the demand curve during peak hours through the implementation of self-sustainable renewable energies to reduce energy generation costs that come mainly from hydraulic sources (MME 2015).

The demand consumption of the country is characterized by a trend that changes depending on the weekday: from Monday to Friday the consumption can be classified as ordinary while Saturday and Sunday can be classified as particular since it is lower than the average. Countrywide the three main points that characterize the demand curve are sunrise (from 5 to 7), the first peak (from 11 to

13) and second peak (18 to 21) in which the second one is the highest due to the lack of sunlight during this period (XM 2020).

b. Desired scenario overview

Domestic electronic devices considered for the model are set considering the investigation made by Hernandez (2017) in which the usual devices for a middle-class family in Colombia were classified in 7 groups and their consumption was modelled depending on their common characteristics.

The groups are heat devices, kitchen devices, lightning systems, televisions, computer, sound and video devices, refrigerators, and laundry devices; their energy consumption varies per hour and per day of the week. Hernandez (2017) made this characterization through a survey to 35 middle-class households in the city of Bogotá. Along with the survey, energy consumption measurements were also applied to the households and showed results mentioned in Figure 9. The investigation proposes a feasible alternative in which the consumers reduce the negative effects of the misuse of electricity by modifying consumption habits to be able to use renewable energy sources appropriately. One of the most important changes would be to replace old electronic devices like light bulbs, fridges, washing machines, etc, for more modern ones that optimize the use of electricity and reduce the significance of their overall impact. However, for the means of this investigation, the electricity consumption modelling would be considering generic domestic devices as done by the author.

c. Estimation of energy consumption per hour of the day

The estimation of the energy consumption per hour of the day was made based on the investigation made by Hernandez (2017). The investigation gives an overview of the generalized consumption of the household per hour of the day as shown in the table below.

Hour	Consumption (W)	Hour	Consumption (W)
0	155.604	12	249.017
1	129.574	13	257.338
2	118.284	14	228.865
3	126.935	15	215.805
4	164.847	16	216.064
5	280.955	17	239.649
6	296.258	18	316.747
7	346.008	19	349.949
8	270.452	20	325.331
9	264.971	21	297.983
10	275.245	22	246.101
11	226.382	23	180.779

Table 1. Hourly Consumption. Source: Author based on (Hernandez, 2017)

However, as for this study we require to understand the consumption per hour of the year, the values were forecasted using stochastic probabilities to the existent information by assigning random probabilities of increasing under three scenarios:

I. Regular consumption

II. Higher consumption during peak hour

III. Higher consumption during the peak hour of the weekend

Each hour of the week had one of those scenarios (I,II,III) assigned as the table below summarizes:

Hour/ Weekday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
0	1	1	1	1	1	2	2
1	1	1	1	1	1	2	2
2	1	1	1	1	1	2	2
3	1	1	1	1	1	2	2
4	1	1	1	1	1	2	2
5	2	2	2	2	2	3	3
6	2	2	2	2	2	3	3
7	2	2	2	2	2	3	3
8	1	1	1	1	1	2	2
9	1	1	1	1	1	2	2
10	1	1	1	1	1	2	2
11	2	2	2	2	2	3	3
12	2	2	2	2	2	3	3
13	2	2	2	2	2	3	3
14	1	1	1	1	1	2	2
15	1	1	1	1	1	2	2
16	1	1	1	1	1	2	2
17	1	1	1	1	1	2	2
18	2	2	2	2	2	3	3
19	2	2	2	2	2	3	3
20	2	2	2	2	2	3	3
21	1	1	1	1	1	2	2
22	1	1	1	1	1	2	2
23	1	1	1	1	1	2	2

Table 2. Hourly scenario set up. Source: Author

A random number from 1 to 10 was assigned to each hour of the day and week from the table above depending on assumptions made of the higher consumptions as

$$y = \{ \begin{array}{c} [8,10]\ if\ x = 3 \\ [4,7] if\ x = 2 \\ [1,3] if\ x = 1 \end{array}$$

Equation 1. Randomization

The percentual increase in the demand was modelled assigning random numbers for specific ranges going from 0% to 5% according to the assumptions previously made:

$$f(x) = \begin{cases} [0\% - 0.9\%]\ if\ y\ between\ 1,3_{(Scenario\ I;Regular\ consumption)} \\ [1\% - 2.9\%] if\ y\ between\ 4,7_{(Scenario\ II;Higher\ consumption\ during\ peak\ hour)} \\ [3\% - 5\%] if\ y\ between\ 8,10_{(Scenario\ 3;Higher\ consumption\ during\ peak\ hour\ weekend)} \end{cases}$$

Equation 2. Incrementals of demand

A hundred simulations were made to estimate the hourly consumption for the year. As the consumption was modelled with stochastic probabilities, there was a 10% of decrease probability assigned to each hour of the year. Then, the hourly consumption summary can be observed in the figure below:

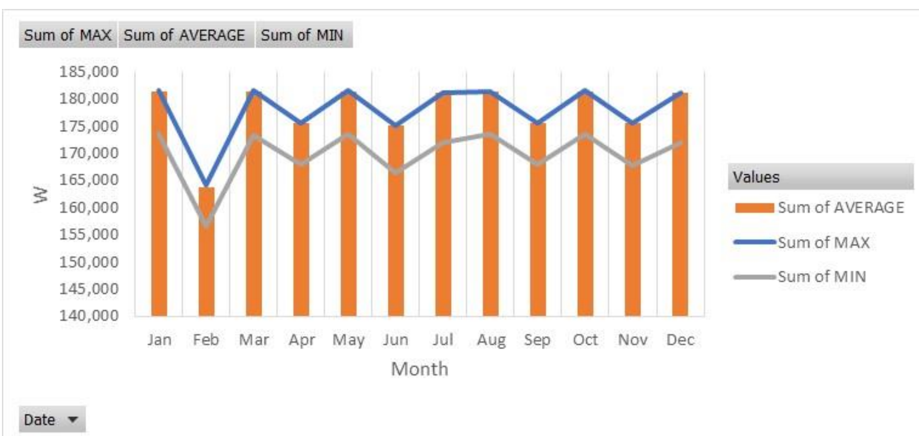

Figure 10. Yearly consumption. Source: Author

It is important to recall that the values forecasted for 2021 were also inflated considering the overall raise in energy demand because of the pandemic.

d. Electricity cost estimation

The electricity measurement per household is done with the counters that accumulate the kWh used during the month. The costs assigned by the grid Operator are consistent with the costs that they inquire to provide the service, thus the cost reflected in the monthly invoice is the product of the kWh consumed by the client times the unitary cost (UC) per kilowatt (Camara de comercio Cali 2016). Colombian framework provides subsidies to households with lower incomes, as well as mandatory contributions of up to 20% of the invoice value for households with higher incomes to compensate the subsidies (MinEnergia 2014). However, for the middle-class households considered for this investigation there is no subside or contribution.

The components of the costs referenced in the invoices are summarized below, all the costs are expressed in terms of unitary kWh:

$$UC: Unitary\ cost\ of\ kWh. Also\ named\ tariff$$

$$G: Cost\ associated\ with\ energy\ generation$$

$$T: Cost\ associated\ with\ the\ transmission\ of\ energy$$

$$C: Cost\ associated\ to\ the\ comercialization\ of\ the\ energy$$

$$D: Cost\ of\ distribution\ of\ the\ energy$$

$$PR: Cost\ of\ loss\ compensation$$

$$R: Cost\ of\ restrictions$$

This way, the Unitary Cost would be composed by all of the costs named before:

$$CU = G + T + D + PR + R$$

Equation 3. Unitary cost per kwh decomposition

For the means of this investigation, the most relevant costs will be the overall CU which for 2021 was estimated at 504,78 COP/kWh since this is the cost over which the monthly savings will be estimated in the model and D+T+C which for 2021 was estimated at 229,42 COP/kWh since this is the cost over which the monthly income will be estimated (Emergente Energia Sostenible 2020)

e. Debt capacity

The assumption made by the current modelling implies that the photovoltaic system supplier 'Electromuebles' is aiming to sell the products on credit to the final consumer with an interest rate of 15% A.E and up for five years. This is a common option provided by multiple solar system providers since the investment that has to be done by households is relatively high if the average income which is around 4.000.000 COP/month is compared to the expense of affording a single solar panel solution which is estimated at 2.040.000 COP. Also, the fraction of debt assumed for the model was of 75% of the total cost of installation of the system, whereas the remaining 25% is assumed by the household equity.

3. Profitability of the implementation of a solar power energy project for a middle-class family in Bogotá

For the current investigation, multiple scenarios were evaluated to identify which one offers the higher feasibility for a 4-member family considering the Colombian background. Each scenario consisted in varying the amount of 260W solar panels to identify the most profitable amount.

Considering that the project is set for a middle-class household in the city of Bogotá that is willing to make profit out of their investment, the Net Present Value will be used as a main evaluation criterion, therefore the project with the highest Net Present Value should be the one adopted by a household in similar circumstances. The financial analysis performed for this investigation was done following the guidelines given by (González, Guzmán y Trujillo 2020)

The evaluation of the model includes a forecasting for 30 years since it coincides with the lifespan of a solar energy power project, which implies that growth rates for revenue and cost had to be considered.

a. Revenue characterization

The revenue for this modelling is composed by two incomes. The first one consists of the yearly savings after consuming the energy provided by the solar panels and the second one consists of the income generated by selling the remaining electricity to the grid. The savings on electricity after installing the photovoltaic system were estimated by calculating the cost of the yearly electricity bill after installing the photovoltaic system and then discounting it from the original price of the yearly electricity expense.

As for the income generated by selling electricity to the grid, the hourly consumption per year had to be modelled as explained in chapter 2c. The assumptions made to estimate this income were: the electricity sold to the grid is only the one generated during the peak radiation hours of the day that go from 11 hours until 14:59 hours and will exclude the consumption of electricity made by the residents of the household. A yearly increase of 1.2% in the electricity consumption was also considered because of COVID impact (UPME 2020)as well as the change in the commercialization price that must be discounted of the selling price per kWh.

The equation below summarizes the revenue for the model:

$$Rev = \sum_{t=1}^{20} SG_t + EBS_t$$

Equation 4. Revenue

$$SG = \sum_{t=1}^{20} G * D * P_t * (1 - C)$$

Equation 5. Income of selling surplus to the grid

$$EBS = \sum_{t=1}^{20} CP_t * P_t - CWP_t * P_t$$

Equation 6. Income of electricity bill savings

$$G = kWh\ generated\ daily$$

$$D = sunlight\ days\ in\ a\ year$$

$$P_t = Price\ per\ kWh\ to\ be\ paid\ to\ the\ electricity\ providers$$

$$C = Comercialization\ cost\ per\ kWh$$

$$CP = Consumption\ without\ panels$$

$$CWP = Consumption\ with\ panels$$

Therefore,

$$Rev = \sum_{t=1}^{20} G_t * D_t * P_t * (1 - C_t) + \sum_{t=1}^{20} CP_t * P_t - CWP_t * P_t$$

Equation 7. Revenue decomposition

b. Cost characterization

The initial investment consisted in a kit of solar panels along with one microinverter per panel, a unitary cost of connection and the labor costs which were estimated at 20% of the individual costs per unit. The costs were estimated considering the price list of the most competitive local provided named 'Electromuebles' and assuming that the average area of a middle-class household in Bogotá is 100 square meters. The capacity of the panels was set to 260W and the space occupied per panel was of 1.63 square meters according to the providers specifications.

$$I = CPP + CPM + CC + (CPP + CPM + CC) * 20\%$$

Equation 8. Initial Investment

$$CPP = Cost\ per\ panel$$

$$CPM = Cost\ per\ microinverter$$

$$CC = Cost\ of\ connection$$

The maintenance cost would be the only yearly expense of the system and it is associated to different expenses that may arise for the adequate manipulation of the equipment.

$$Costs = \mathrm{N} * \sum_{t=1}^{20} Maint_t(1 + Inflation_t)$$

Equation 9. Costs

$$Rep = Yearly\ Reposition\ cost$$

$$Maint = Yearly\ Maintenance\ cost$$

$$MaintIncrease = Yearly\ Percentage\ of\ increase\ of\ maintenance\ cost$$

$$N = Number\ of\ solar\ panels\ installed$$

c. Debt amortization

The debt amortization was estimated by following the Colombian standards for 'free investment loans' in which the maximum payback period is 5 years. The yearly payment was calculated using the loan payment formula as follows:

$$P = \frac{i * I}{1 - (1 + i)^{-n}}$$

Equation 10. Yearly payment

$$i = Loan\ interest\ rate$$

$$n = Number\ of\ payments$$

It is important to recall that the interest is calculated based on the remaining debt per period and the amortization payment given by the formula should exclude those interests.

d. Assumption table

As stated by (González, Guzmán y Trujillo 2020), each project valuation must contain an assumption table to forecast the balance sheet, P&L and cash flows and thus be able to make the best financial decision for the project. Therefore, two different assumption tables are shown, each one with a different objective but all under the initial assumption of purchasing a system composed of three panels which corresponds to the optimal number of panels after the corresponding iterations in the model.

The first table corresponds to the yearly assumptions that are independent from the number of panels:

Yearly assumptions								
Year	0	1	2	3	4	5	29	30
Consumption (kWh/year)		2,134.6	2,177.3	2,220.9	2,265.3	2,310.6	3,716.5	3,790.8
Electricity Cost (COP/kWh)		$ 504.8	$ 514.9	$ 525.2	$ 535.7	$ 546.4	$ 878.8	$ 896.4
Electricity price for selling to grid (COP/kWh)		$ 229.4	$ 234.0	$ 238.7	$ 243.5	$ 248.3	$ 399.4	$ 407.4
Inflation Rate		2%	2%	2%	2%	2%	2%	2%
Bank Loan Interest Rate		15%	15%	15%	15%	15%	15%	15%
Loan percentage		75%	75%	75%	75%	75%	75%	75%
Equity (household) cost of capital		0.17%	0.17%	0.17%	0.17%	0.17%	0.17%	0.17%

Table 3. Yearly assumptions

And the second table corresponds to the yearly assumptions considering that the system will be composed by three solar panels:

Yearly assumptions (under 3 panel system)								
Year	0	1	2	3	4	5	29	30
Peak power installed (W)		780	780	780	780	780	780	780
Generation (kWh)		1,043	1,064	1,086	1,107	1,129	1,817	1,853
Load (kWh)		2,135	2,177	2,221	2,265	2,311	3,716	3,791
Self consumption (kWh/year)		785	801	817	833	850	1,367	1,395
Sold to grid (kWh/year)		258	263	268	274	279	449	458
Residual Load (kWh/year)		1,349	1,376	1,404	1,432	1,461	2,349	2,396
Cost w/o panels (COP/year)		$ 1,077,525	$ 1,099,075	$ 1,121,057	$ 1,143,478	$ 1,166,348	$ 1,875,997	$ 1,913,517
Revenue (COP/year)		$ 59,204	$ 60,388	$ 61,596	$ 62,827	$ 64,084	$ 103,075	$ 105,137
Residual Cost (COP/year)		$ 681,110	$ 694,732	$ 708,627	$ 722,799	$ 737,255	$ 1,185,829	$ 1,209,546
Savings due to project (COP/year)		$ 455,619	$ 464,731	$ 474,026	$ 483,506	$ 493,176	$ 793,243	$ 809,108
Revenue from sale (COP/year)		$ 239,374	$ 244,162	$ 249,045	$ 254,026	$ 259,106	$ 416,756	$ 425,092
Loan Repayment (COP)		$ (1,196,788)	$ (1,196,788)	$ (1,196,788)	$ (1,196,788)	$ (1,196,788)		
Electricity savings (w/ inflation)		$ 455,619	$ 464,731	$ 474,026	$ 483,506	$ 493,176	$ 793,243	$ 809,108
Maintenance costs (w/ inf)		$ (90,000)	$ (91,800)	$ (93,636)	$ (95,509)	$ (97,419)	$ (156,692)	$ (159,826)

Table 4. Yearly assumptions under three panel system

e. Forecasted P&L

The presented P&L analysis also corresponds to the scenario in which three panels were included in the system. It is important to note that as this is a project that counts with government incentives, there is no tax charged to the income generated nor additional charges per additional earnings of the household.

Year	0	1	2	3	4	5	29	30
Selling surplus to the grid		$ 59,204	$ 60,388	$ 61,596	$ 62,827	$ 64,084	$ 103,075	$ 105,137
Electricity bills savings		$ 396,415	$ 404,343	$ 412,430	$ 420,679	$ 429,092	$ 690,168	$ 703,971
Revenue		**$ 455,619**	**$ 464,731**	**$ 474,026**	**$ 483,506**	**$ 493,176**	**$ 793,243**	**$ 809,108**
Maintenance		$ (90,000)	$ (91,800)	$ (93,636)	$ (95,509)	$ (97,419)	$ (156,692)	$ (159,826)
Costs		**$ (90,000)**	**$ (91,800)**	**$ (93,636)**	**$ (95,509)**	**$ (97,419)**	**$ (156,692)**	**$ (159,826)**
Gross Profit		**$ 365,619**	**$ 372,931**	**$ 380,390**	**$ 387,997**	**$ 395,757**	**$ 636,551**	**$ 649,282**
Additional expenses per income		$ -	$ -	$ -	$ -	$ -	$ -	$ -
EBIT		**$ 365,619**	**$ 372,931**	**$ 380,390**	**$ 387,997**	**$ 395,757**	**$ 636,551**	**$ 649,282**
Interests		$ 601,773	$ 512,521	$ 409,880	$ 291,844	$ 156,103		
Profit		**$ (236,154)**	**$ (139,590)**	**$ (29,491)**	**$ 96,153**	**$ 239,655**	**$ 636,551**	**$ 649,282**

Table 5. 30 year P&L Analysis for 3 panel system

f. Forecasted Cash flows

The forecasted cash flows were all done by following the assumptions previously referenced and are shown in the table below.

Year	0	1	2	3	4	5	6	25	26	30
Cash Flows	-1,337,273	-831,169	-823,857	-816,398	-808,791	-801,031	403,673	588,075	0	0
Present Value	-1,337,273	-829,759	-821,063	-812,249	-803,314	-794,256	399,579	563,625	0	0

Table 6. Forecasted cash flows

g. NPV valuation

One of the criteria utilized to evaluate the feasibility of the project is going to be by estimating the Net Present Value considering that, since it is a personal investment made by a single household, what would be more convenient would be to generate as much profit as possible during the lifetime of the project which was estimated at 20 years.

To determine the NPV for each of the scenarios proposed below the following formula was used:

$$NPV = \sum_{t=1}^{20} \frac{F_t}{(1+i)^t}$$

Equation 11. Net Present Value

$$F_t = Cash\ flow\ in\ the\ t\ period$$

$$i = Discount\ rate$$

I. Results

Seven simulations were done to obtain the highest NPV for the project. The results can be shown in the table below:

Number of panels	NPV [000's COP]	Investment [000's COP]	Loan amount [000's COP]
2	3,671.92	3,694.70	2,771.03
3	4,145.21	5,349.09	4,011.82
4	3,957.36	7,003.48	5,252.61
5	3,548.29	8,657.87	6,493.40
6	3,055.22	10,312.26	7,734.20
7	2,520.86	11,966.65	8,974.99

Table 7. Results of Simulations. Source: Author

As observed, the best project would be installing 3 solar panels of 260W, which would provide an NPV of 4M COP in the 30-year horizon proposal and a total investment of 5,3M COP. This option would be feasible for a middle-class household since the total area occupied by the 3 solar panels would be 4.89 square meters, which goes in line with the 100 square meters average area of a middle-class household in Bogotá. Also, the Levelized Cost of Energy was estimated at 309.6 COP/kwh, which is 34% above the regular electricity selling price per kwh and could be further used to compare between different energy production sources (for instance the normal cost per kwh stablished in 504.78 COP/kwh).

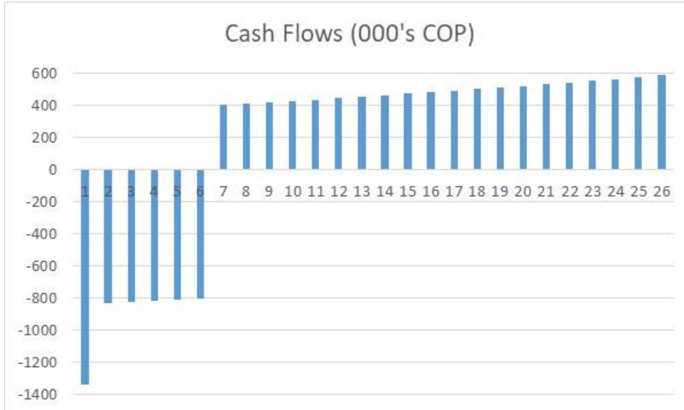

Figure 11. Estimated Cash flows. Source: Author

Within this scenario there would be no batteries available for the use of the household and therefore the only energy that would be available to sell to the grid would be the one produced during the sunlight hours of the day which go from 10 until 17 hours excluding the consumption of the family during those hours. Also, there would be an internal rate of return of 4.5% which is assumed as positive since the household would be having extra income of around 245.000 COP per year out of their investment as well as the positive environmental impact coming out of the project. The payback period would be the sixth year of operation of the project.

4. Conclusions

It is important to consider that even with a Net Present Value higher than 4M COP this project is set to be done in familiar residences and afforded by middle-class families in Bogotá, whose monthly income is 4.000.000 COP which is equivalent to €900. This situation makes the project more complex since the aim of the project itself is to generate economic profit besides of the environmental impact that would come along with an autonomous solar power system in the long term. The reduction of the cost of the electricity bill given the availability of electricity coming from a renewable energy source during a considerable fraction of the day and the extra income coming from the injection of electricity to the grid since the electricity to be sold would not just be produced during peak hours but during all the sunlight hours of the day are a big incentive for this kind of projects. However, it is important to consider that this kind of systems are also aiming to increase the trust in the system, which means having electricity available during potential shortages. In this way, it would be useful to consider including a battery in the system instead of just using panels during sunlight hours, that way it would be possible to use electricity during nighttime instead of selling surplus to the grid.

Given the elevated costs of this project when situating it in the Colombian economy, there would be other alternatives that could be more feasible for people to implement this type of solutions in their households. One of them could be for instance proposing to urban housing companies to implement solar power solutions in the design of their houses or apartments for people to be able to generate more income or savings in electricity and generate an environmental impact at the same time. It is more feasible that households decide to spend more money on their own house rather than making a big investment after they have already bought a new property. Another advantage of this alternative would be the possibility of reducing the interest rate and extending the amortization period since the loan that would be requested would not be for a free investment but for a property acquisition.

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Contents

INTRODUCTION..4

1. Bogota´s solar power energy background..5

   a. General overview 5

   b. Government regulations 6

   c. Radiation advantages because of localization Colombia's geographic location..................7

d. Historic radiation measurements in the area 9

e. Solar panel market overview 9

I. Isolated systems 9

II. Hybrid systems 10

III. Systems connected to the grid 11

2. Characterization of the consumption habits of a middle-class family located in Bogotá, Colombia 11

a. Generalities of domestic electrical system 11

b. Desired scenario overview 13

c. Estimation of energy consumption per hour of the day 13

d. Electricity cost estimation 16

e. Debt capacity 17

3. Profitability of the implementation of a solar power energy project for a middle-class family in Bogotá 17

a. Revenue characterization 18

b. Cost characterization 19

c. Debt amortization 20

d. Assumption table 21

e. Forecasted P&L 22

f. Forecasted Cash flows 22

g. NPV valuation 22

I. Results 23

4. Conclusions 24

Bibliography 26

5. APPENDIX 30

a. Colombian energy demand curve 31

b. Incremental Cash Flows 32

c. Payback year 33

d. Loan repayment estimations 34

e. LCOE Cash Flows 35

f. Consumption simulations (overview of the year) 36

g. Radiation estimation 37

Table 1. Hourly Consumption. Source: Author based on (Hernandez, 2017) 14
Table 2. Hourly scenario set up. Source: Author 14
Table 3. Yearly assumptions 21
Table 4. Yearly assumptions under three panel system 21
Table 5. 30 year P&L Analysis for 3 panel system 22
Table 6. Forecasted cash flows 22
Table 7. Results of Simulations. Source: Author 23

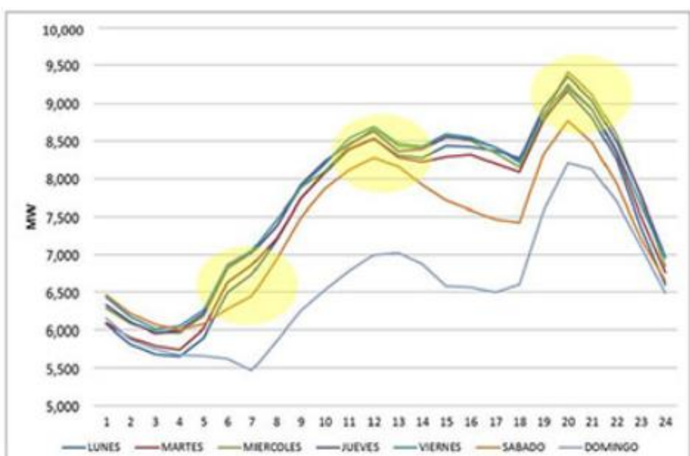
Figure 1. Electricity production breakdown. Source: Author based in (Ritchie y Roser 2019) 6
Figure 2. Energy Consumption trends. Source: Source: Author based in (Ritchie y Roser 2019) 6
Figure 3. Radiation per zone in Colombia. Source: (Global solar atlas s.f.) 8
Figure 4. Photovoltaic capacity in Colombia. Source: Author based in (Statista 2021). 8
Figure 5. Photovoltaic System Power in Bogotá. Source: Authors based in (European Commission 2020) 9
Figure 6. Isolated system components. Source: Author based in (Sun Supply 2020) 10

Figure 7. Hybrid system components. Source: Author based in (Sun Supply 2020) 10
Figure 8. Components of a system connected to the grid. Source: made by Author based in (Sun Supply 2020).. 11
Figure 9. Average consumption per home per hour of the day. Source: Author based on (Hernandez, 2017) 12
Figure 10. Yearly consumption. Source: Author.. 15
Figure 11. Estimated Cash flows. Source: Author 24

Annex 1. Colombian energy demand Curve. Source (XM, 2020) 31
Annex 2. Incremental cash flows.. 32
Annex 3. Payback year.. 33
Annex 4. Loan repayment estimations.. 34
Annex 5. LCOW Cash Flows 35
Annex 6. Consumption simulations.. 36
Annex 7. Radiation estimation 37

5. APPENDIX

a. Colombian energy demand curve



Annex 1. Colombian energy demand Curve. Source (XM, 2020)

b. Incremental Cash Flows

Year	(Equity) Investment	Electricity savings (w/ inflation)	Maintenance costs (w/ inf)	Loan repayment	CF	PV(CF)	NPV	IRR
0	-1,337,273				-1,337,273	-1,337,273	4,145,213.27	4.6%
1		455,619	-90,000	-1,196,788	-831,169	-829,759		
2		464,731	-91,800	-1,196,788	-823,857	-821,063		
3		474,026	-93,636	-1,196,788	-816,398	-812,249		
4		483,506	-95,509	-1,196,788	-808,791	-803,314		
5		493,176	-97,419	-1,196,788	-801,031	-794,256		
6		503,040	-99,367	0	403,673	399,579		
7		513,101	-101,355	0	411,746	406,879		
8		523,363	-103,382	0	419,981	414,313		
9		533,830	-105,449	0	428,380	421,882		
10		544,506	-107,558	0	436,948	429,589		
11		555,397	-109,709	0	445,687	437,437		
12		566,504	-111,904	0	454,601	445,429		
13		577,835	-114,142	0	463,693	453,566		
14		589,391	-116,425	0	472,967	461,852		
15		601,179	-118,753	0	482,426	470,290		
16		613,203	-121,128	0	492,075	478,882		
17		625,467	-123,551	0	501,916	487,630		
18		637,976	-126,022	0	511,954	496,539		
19		650,736	-128,542	0	522,193	505,610		
20		663,750	-131,113	0	532,637	514,847		
21		677,025	-133,735	0	543,290	524,253		
22		690,566	-136,410	0	554,156	533,830		
23		704,377	-139,138	0	565,239	543,583		
24		718,465	-141,921	0	576,544	553,513		
25		732,834	-144,759	0	588,075	563,625		
26		747,491	-147,655	0	0	0		
27		762,440	-150,608	0	0	0		
28		777,689	-153,620	0	0	0		
29		793,243	-156,692	0	0	0		
30		809,108	-159,826	0	0	0		

Annex 2. Incremental cash flows

c. Payback year

Year	Accum CF	Payback year
0	-1,337,273	
1	-2,168,442	
2	-2,992,299	
3	-3,808,698	
4	-4,617,488	
5	-5,418,519	
6	-5,014,847	18
7	-4,603,101	
8	-4,183,120	
9	-3,754,739	
10	-3,317,791	
11	-2,872,104	
12	-2,417,503	
13	-1,953,810	
14	-1,480,844	
15	-998,418	
16	-506,343	
17	-4,427	
18	507,527	
19	1,029,721	
20	1,562,358	
21	2,105,648	
22	2,659,804	
23	3,225,043	
24	3,801,587	
25	4,389,661	
26	4,389,661	
27	4,389,661	
28	4,389,661	
29	4,389,661	
30	4,389,661	

Annex 3. Payback year

d. Loan repayment estimations

Loan						
Year	0	1	2	3	4	5
Loan	4,011,819.04	3,416,804	2,732,536	1,945,629	1,040,685	0
Interest		601,772.86	512,520.58	409,880.47	291,844.34	156,102.78
Payment	0	595,015.16	684,267.43	786,907.55	904,943.68	1,040,685.23

Annex 4. Loan repayment estimations

e. LCOE Cash Flows

Revenue (w/ inf)	CF	PV(CF)	NPV
	-1,337,273	-1,337,273	0.00
323,093	-963,695	-962,060	
329,555	-959,033	-955,781	
336,146	-954,278	-949,428	
342,869	-949,428	-942,999	
349,726	-944,481	-936,493	
356,721	257,353	254,744	
363,855	262,501	259,398	
371,132	267,751	264,137	
378,555	273,106	268,962	
386,126	278,568	273,876	
393,849	284,139	278,879	
401,726	289,822	283,974	
409,760	295,618	289,162	
417,955	301,531	294,445	
426,314	307,561	299,824	
434,841	313,712	305,302	
443,537	319,987	310,879	
452,408	326,386	316,559	
461,456	332,914	322,342	
470,685	339,572	328,231	
480,099	346,364	334,227	
489,701	353,291	340,333	
499,495	360,357	346,550	
509,485	367,564	352,882	
519,675	374,915	359,328	
530,068	0	0	
540,670	0	0	
551,483	0	0	
562,513	0	0	
573,763	0	0	

Annex 5. LCOW Cash Flows

f. Consumption simulations (overview of the year)

Date / Iteration	1	2	99	100	MAX	MIN	AVERAGE	kwh
1/1/2021 0:00	156.38	156.86	156.27	156.70	156.82	154.26	156.31	0.16
1/1/2021 1:00	129.75	130.48	129.58	130.23	129.86	128.37	129.99	0.13
1/1/2021 2:00	118.68	117.77	119.41	119.43	119.04	117.25	118.76	0.12
1/1/2021 3:00	127.95	126.55	127.81	126.10	127.85	125.67	127.29	0.13
1/1/2021 4:00	165.90	165.16	166.08	165.37	166.01	163.41	165.55	0.17
1/1/2021 5:00	267.83	286.23	284.93	284.22	285.56	267.83	285.35	0.29
1/1/2021 6:00	281.51	299.43	292.73	290.77	299.32	281.51	300.59	0.30
1/1/2021 7:00	319.52	349.56	355.83	355.61	342.16	319.52	350.88	0.35
1/1/2021 8:00	270.53	272.91	273.14	271.83	272.54	267.76	271.46	0.27
1/1/2021 9:00	266.44	267.58	265.42	265.38	266.11	262.48	265.97	0.27
1/1/2021 10:00	276.82	275.43	275.11	277.22	276.58	272.97	276.42	0.28
1/1/2021 11:00	222.98	230.90	220.30	232.80	231.59	219.45	230.27	0.23
12/31/2021 9:00	270.09	271.00	270.59	269.96	271.93	256.79	268.35	0.27
12/31/2021 10:00	276.07	277.39	278.63	272.67	283.61	267.03	278.11	0.28
12/31/2021 11:00	227.58	233.03	227.08	231.19	231.28	222.65	229.03	0.23
12/31/2021 12:00	251.10	249.59	249.61	250.66	250.20	242.40	252.01	0.25
12/31/2021 13:00	232.92	257.39	265.00	262.53	263.48	232.92	260.24	0.26
12/31/2021 14:00	218.89	230.48	230.82	232.25	227.48	218.89	231.25	0.23
12/31/2021 15:00	218.96	216.86	221.76	215.56	218.23	209.25	218.45	0.22
12/31/2021 16:00	215.81	217.90	218.48	216.21	220.27	210.67	218.63	0.22
12/31/2021 17:00	240.43	241.23	243.36	241.27	240.30	232.37	242.40	0.24
12/31/2021 18:00	314.24	322.40	325.91	321.00	323.92	307.57	320.72	0.32
12/31/2021 19:00	327.00	356.15	353.36	351.90	359.83	327.00	353.66	0.35
12/31/2021 20:00	310.34	327.56	324.03	333.94	327.25	310.34	328.84	0.33
12/31/2021 21:00	293.90	305.14	302.38	305.39	302.17	289.42	300.74	0.30
12/31/2021 22:00	246.48	247.37	247.44	248.09	241.42	239.86	248.73	0.25
12/31/2021 23:00	181.99	181.67	182.85	182.87	182.10	175.18	182.46	0.18

Annex 6. Consumption simulations

g. Radiation estimation

time	Date	P	Gb(i)	Gd(i)	Gr(i)	time	Date	P	Gb(i)	Gd(i)	Gr(i)	time	Date	P	Gb(i)	Gd(i)	Gr(i)	Hour	Average P
20130101:	2013/01/0	0.00	0.00	0.00	0.00	20140101:	2014/01/0	0.00	0.00	0.00	0.00	20150101:	2015/01/0	0.00	0.00	0.00	0.00	6	0
20130101:	2013/01/0	0.00	0.00	0.00	0.00	20140101:	2014/01/0	0.00	0.00	0.00	0.00	20150101:	2015/01/0	0.00	0.00	0.00	0.00	7	0
20130101:	2013/01/0	30.85	0.00	50.93	0.01	20140101:	2014/01/0	31.65	0.00	51.92	0.01	20150101:	2015/01/0	37.91	0.00	59.91	0.01	8	33.47
20130101:	2013/01/0	223.53	78.72	200.48	0.05	20140101:	2014/01/0	339.09	352.29	71.35	0.07	20150101:	2015/01/0	348.85	344.42	90.19	0.07	9	303.8233
20130101:	2013/01/0	539.49	578.48	82.89	0.11	20140101:	2014/01/0	539.64	577.48	83.89	0.11	20150101:	2015/01/0	555.34	571.50	105.86	0.11	10	544.8233
20130101:	2013/01/0	680.24	758.88	91.45	0.14	20140101:	2014/01/0	682.31	759.89	92.45	0.14	20150101:	2015/01/0	702.75	753.85	116.57	0.14	11	688.4333
20130101:	2013/01/0	766.12	878.58	96.03	0.16	20140101:	2014/01/0	767.47	879.59	97.04	0.16	20150101:	2015/01/0	790.74	871.48	124.32	0.16	12	774.7767
20130101:	2013/01/0	795.90	924.71	97.62	0.16	20140101:	2014/01/0	797.13	925.73	99.66	0.16	20150101:	2015/01/0	821.91	917.55	126.08	0.17	13	804.98
20130101:	2013/01/0	770.87	893.38	96.25	0.16	20140101:	2014/01/0	772.41	895.44	98.30	0.16	20150101:	2015/01/0	796.85	885.12	124.89	0.16	14	780.0433
20130101:	2013/01/0	267.70	23.01	315.05	0.06	20140101:	2014/01/0	698.83	790.81	93.98	0.14	20150101:	2015/01/0	715.41	776.16	119.72	0.14	15	560.6467
20130101:	2013/01/0	564.63	617.54	84.62	0.11	20140101:	2014/01/0	568.56	621.81	85.69	0.11	20150101:	2015/01/0	576.49	602.61	109.57	0.11	16	569.8933
20130101:	2013/01/0	0.00	0.00	0.00	0.00	20140101:	2014/01/0	0.00	0.00	0.00	0.00	20150101:	2015/01/0	0.00	0.00	0.00	0.00	21	0
20130101:	2013/01/0	0.00	0.00	0.00	0.00	20140101:	2014/01/0	0.00	0.00	0.00	0.00	20150101:	2015/01/0	0.00	0.00	0.00	0.00	22	0
20130101:	2013/01/0	0.00	0.00	0.00	0.00	20140101:	2014/01/0	0.00	0.00	0.00	0.00	20150101:	2015/01/0	0.00	0.00	0.00	0.00	23	0
20130101:	2013/01/0	0.00	0.00	0.00	0.00	20140101:	2014/01/0	0.00	0.00	0.00	0.00	20150101:	2015/01/0	0.00	0.00	0.00	0.00	24	0

Annex 7. Radiation estimation