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Study on the profitability of residential solar PV system under the Madagascar's New Energy Policy (NPE).

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Abstract— *Madagascar recently adopted a new energy policy allowing Electricity Market Liberalization. Energy injection into the grid by residential small photovoltaic installations will then soon be possible. However, installing a solar system remains an expensive investment and it is essential to carry out preliminary studies to obtain a good benefit from it. In this context, this work deals with parametric studies and the specific impacts of three key factors such as the feed-in tariff, the electricity consumption, and the installed power peak on their profitability. The results indicate that a profit is possible with the direct injection of excess energy at a price of at least 600 MGA/kWh,*

Keywords— Residential photovoltaic systems, grid injection, Madagascar, Profitability, Net present value

1. Introduction

Fossil fuels currently fulfill over 80% of the world's energy needs [1]. These resources are subject to two disadvantages: the depletion and the greenhouse gas (GHG) emission which leads to global warming. About 26% of global GHG emissions come from the energy sector [2].

Face to this fossil fuel depletion and the climate change, the primary challenge is the adoption of cleaner and sustainable energy alternatives to satisfy the growing energy demands. This progressive shift is commonly called the "Energy Transition."

As the transition to cleaner energy sources unfolds gradually, its pace and nature may vary from one country to another. In Madagascar, for instance, a significant portion of electricity production still relies on thermal power plants fueled by heavy fuel oil or diesel. According to September 2021 statistics [3], thermal sources account for 70.15% of installed electrical power, while hydroelectric sources accounts for 25.13%. Solar PV represents only 4.04% with biomass, wind, and other sources combined making up 0.68%.

Energy decentralization, along with the promotion of microgrids and small-scale energy sources, offers a pathway to enhance energy self-sufficiency in a sustainable manner. Solar home installations, hold significant potential in this regard, especially given the preference for grid injection under Madagascar's New Energy Policy. In light of this, our study presents a preliminary analysis of the profitability of solar home installations connected to the grid in Antananarivo.

2. Method of calculation and hypothesis

Our study focuses on a typical household in Antananarivo with five members and 1200 kWh annual electricity consumption [4]. The household intends to install a grid-connected PV photovoltaic system. We analyze four different scenarios:

- Scenario 1: The household relies entirely on grid electricity and sells all generated solar energy directly to the grid during the day (without storage).
- Scenario 2: Similar to Scenario 1, but with the addition of storage, allowing the household to sell solar energy to the grid both during the day and at night.
- Scenario 3: The household utilizes solar energy during the day with the help of storage, avoiding grid electricity usage, and switches to grid electricity at night.
- Scenario 4: The household uses solar energy during the day, selling excess energy to the grid, and utilizes stored solar energy during the night.

3. Financial study of a solar PV project for grid injection

3.1. Money flows [5]:

Calculating cash flows entails annually monitoring all expenses (outflows) and revenues (inflows) generated by the project. For the purposes of our analysis, we will assume that the projects under study were neither financed through loans nor subsidized. The total outgoing cash flow in year n for an on-grid PV installation is determined as follows:

$$F_{out,n} = C_{E\&E}(1+i)^n + C_{cons,n}(1+\Delta p_{cons})^n \quad (1)$$

$F_{out,n}$ the total outflow at year n ;

$C_{E\&E}$: Annual operation and maintenance cost;

$C_{cons,n}$: Annual cost of energy consumption drawn from the grid at year ;

i : Annual constant inflation rate of $C_{E\&E}$;

Δp_{cons} : Annual constant escalation rate of the unit price (per KWh) p_{cons} of energy withdrawn from the grid

Note: At year 0, the total outflow $F_{out,0}$ is equal to the initial investment.

Total incoming flow: the total incoming flow at year n in the case of a solar PV installation connected to the grid is :

$$F_{in,n} = R_{inj,n}\left(1+\Delta p_{inj}\right)^n + C_{éco,n}(1+\Delta p_{cons})^n \quad (2)$$

$F_{in,n}$: total inflow at year n ;

$R_{inj,n}$ Annual income from the sale of energy injected into the grid at year n;

Δp_{inj} : Annual constant inflation rate of the unit price (per KWh) p_{inj} of energy fed into the grid ;

$C_{eco,n}$ Annual cost savings over the year n thanks to self-consumption. This is the cost of the energy consumed per year n if all of it had been supplied by the grid [6].

Note: at year 0, the total inflow $F_{ent,0}$ is zero : $F_{ent,0} = 0$.

Annual revenues and costs are given by :

$$C_{cons} = \sum_{k=1}^{12}\left(E_{cons,k} \times p_{cons,k}\right); \quad (3)$$

$$C_{eco} = \sum_{k=1}^{12}\left(E_{totcons,k} \times p_{cons,k}\right); \quad (4)$$

$$R_{inj} = \sum_{k=1}^{12}\left(E_{inj,k} \times p_{inj}\right) \quad (5)$$

$E_{cons,k}$: Energy consumed from the network in the month;

$E_{totcons,k}$: Total energy consumed in the month; $p_{cons,k}$ unit price (of the KWh) of the energy withdrawn from the grid in the month ;

p_{inj} : unit price (of the KWh) of the sold energy injected to the electrical network. In the following, we will assume that this price is fixed and independent of the quantity of energy injected.

Net cashflow (NCF): This is the difference between the total incoming flow and the total outgoing flow. In this case, the NCF at year n is :

$$F_n = F_{in,n} - F_{out,n} \quad (6)$$

3.2. Financial Sustainability Indicator

The objective of a financial feasibility study is to calculate criteria or indices indicating whether the project is profitable or not. In this study, the financial viability indicator calculated will be the Net Present Value (NPV). It is equal to the sum, over the project's life span, of the discounted cashflows [5] [7]:

$$NPV = \sum_{n=0}^{N} \frac{F_n}{(1+d)^n} \quad (7)$$

F_n : NCF at year ;

N : project's life span;

d : the constant annual discount rate. In the practical case, the discount rate is taken to be equal to the opportunity cost of capital [7] which is the average rate of return that the investor could have if he invested his resources in another project.[8] In other words, it is the rate of return required by the investor [9].

If the $NPV > 0$ then the project's profitability is higher than the required rate d.

In the opposite case ($NPV = 0$ or $NPV < 0$), the profitability is equal to or lower than the rate d required by the contractor [10]. Moreover, if one has to choose between projects of the same duration, the one with the highest NPV is chosen [10].

4. Input data for the study

4.1. Load profile

The load profile used in this study was generated from the Sunny Design online software. The consumption curve corresponds to a 5 persons household with an annual consumption of 1200 kWh/year.

4.2 Financial inputs

MATLAB programming software was used.

The feasibility analyses of the studied scenarios have been done with the input parameters of Table 1. The costs except the replacement of batteries and inverters are assumed to be negligible. The value of the injection tariff was taken to be slightly lower than that of the 1st bracket of JIRAMA's economic tariff 20. On the other hand, it is customary, in case of lack of information, to attribute to the rate Δp_{inj} and Δp_{cons} the same value as the inflation rate i [13] [14].

Table 1 Main input parameters for the financial feasibility analyses of the systems studied.

Input parameters for the feasibility analyses	Values
Life of the project	25 years
Battery replacement	year 5,10,15, and 20
Replacement of inverters	year 15 [11]
Electricity injection (or sale) tariff	300 MGA/kWh
Tariff for electricity drawn from the grid	Economic Tariff 20
VAT tax	20%
Discount rate	5% [8]
Inflation rate $\boldsymbol{i}$	6,9% [12]
Injection price escalation rate $\Delta \boldsymbol{p}_{inj}$	6,9%
Escalation rate of the grid consumption price $\Delta \boldsymbol{p}_{cons}$	6,9%

4.3 Sizing :

PVSYST , Software for sizing and simulation of photovoltaic installations, was used.

Table 2 presents the characteristics of the PVSYSTEMS for each scenario. In the case of scenarios 2 and 3, the idea was to size the batteries to have a 7-hour autonomy. For scenario 4, the batteries were sized for 1 day of autonomy

Table 1 Characteristics of the PV installations modelled according to the imposed scenarios

Scenarios	Equipment	Brand	Model	Number	Unit Price (MGA) [15]
1,2,3 and 4	250Wp/25V modules Si-mono	Einnova Solarline	ESM 250W 60 cells	04	453 750
1,2,3 and 4	Inverter : 800WAC/45-95V	Siemens	SPN 1000D	01	264 000
2,3	Battery : 12V/26Ah Pb sealed AGM,	MK Battery	MK 8GU1 Gel	07	176 000
4	Battery : 12V/26Ah Pb sealed AGM	MK Battery	MK 8GU1 Gel	14	176 000

4.4 Values taken for parametric analyses

Table 3 Values taken for parametric analyses,

Parameter to be varied	Minimum value	Increment	Maximum value
The injection price	100 MGA/kWh	100 MGA	1000 MGA/kWh
Annual consumption	400kWh/year	200kWh	1800kWh/year
Installed capacity	2 PV modules	1 PV module	7 PV modules

Table 4 Choice of inverter according to the number of PV modules installed,

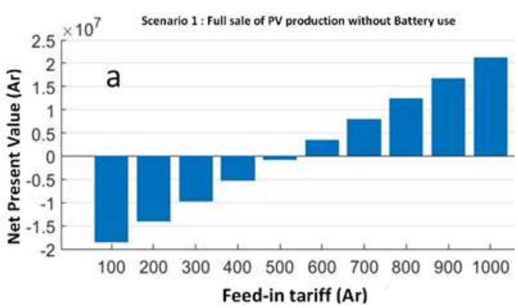
Number of tickets	Inverter	Brand	Model	Number	Unit Price (MGA)
2	400WAC	Hoymiles	HM-400	01	132 000
3	600WAC	SMA	Sunny Boy SWR 700 Medium	01	198 000
4	800WAC	Siemens	SPN 1000D	01	264 000
5	1000WAC	SMA	Sunny Boy SWR 1100LV	01	847 000
6	1200WAC	Sun Power	SP1200-400	01	1 016 400
7	1400WAC	Sunways	NT1800	01	1 185 800

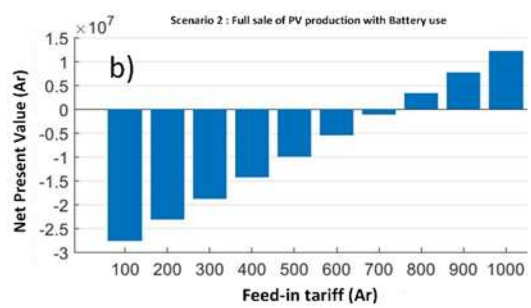
Keeping the other parameters constant, we systematically altered each variable listed in Table 3 to assess its impact on the profitability of individual projects. Given the inherent uncertainty associated with some of the parameters, particularly those with varying degrees of uncertainty, our analysis focuses primarily on understanding the directional changes in profitability. Consequently, the figures presented should be interpreted as indicative trends rather than precise values. Table 4 outlines the selection criteria for inverters based on the installed capacity.

5. Parametric Studies

5.1. Variation of the injection price

According to the Figure 1.a), Figure 1.b) and Figure 1.d), the profitability of scenarios 1, 2, and 4 increase as the fixed injection price increases.





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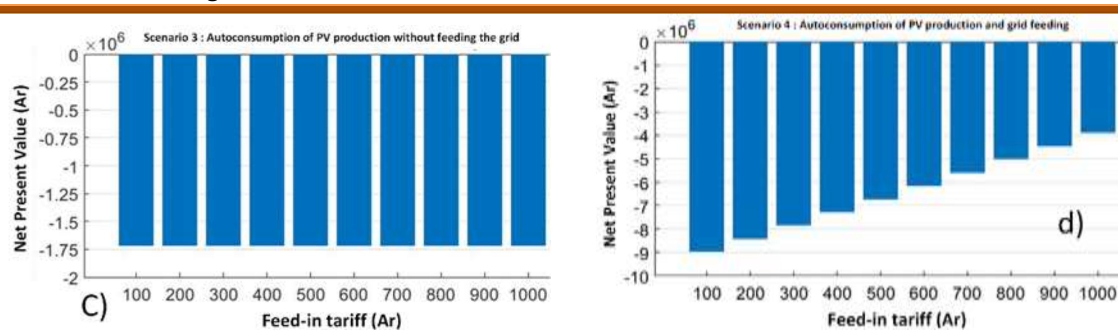


Figure 1 Variation of NPV as a function of injection price for Scenarios 1, 2, 3 and 4.

This is because the increase in the fixed selling price increases the annual revenue from the sale of electricity, and thus increases the NPV of the project. Scenario 3 at Figure 1.c), on the other hand, is not affected by the variation in the injection price. Indeed, as there is no sale of the injections, the NPV is then independent of the grid injection price.

From the results, we were also able to establish the order of scenario choices, based on the injection price:

Table 5 Order of scenario choices based on injection price.

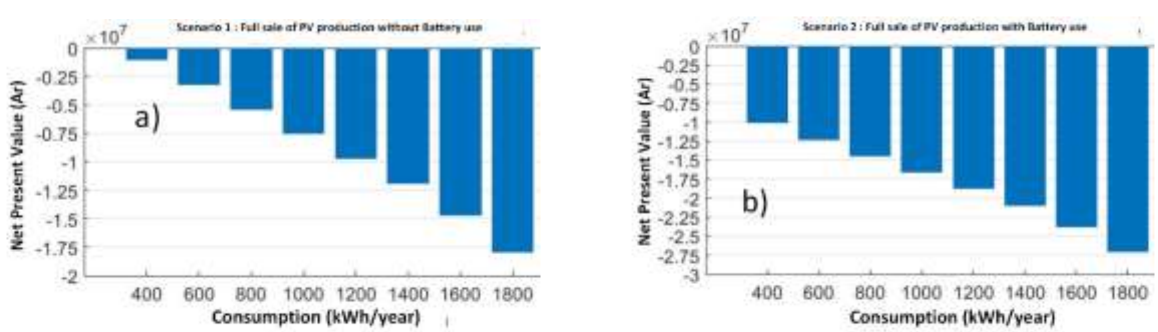
Injection price MGA/kWh	1er choice	2ème choices	3ème choices	4ème choices
Less than 400	3	4	1	2
400	3	1	4	2
500	1	3	4	2
600	1	3	2	4
700	1	2	3	4
As from 800	1	2	3	4

The first choice represents the most profitable scenario while the last choice represents the least profitable scenario. A black box means that the choice is not profitable.

According to the Table 5 and following the constraints imposed in this study, an average Malagasy household can only benefit from the use of a grid-connected PV system if all of the output is injected and sold at a price equal to or greater than 600MGA/kWh.

5.2. Influence of a change in the electricity consumption

According to the Figure 2.a) and Figure 2.b), the profitability of scenarios 1 and 2 decrease as consumption increases. This is because the bills to be paid to JIRAMA also increase with consumption, thus decreasing the NPV of the project. On the other hand, in Figure 2.c) and Figure 2.d), the higher the consumption, the more likely scenarios 3 and 4 are to be profitable. Indeed, the higher the consumption, the higher the bills avoided thanks to self-consumption, which are counted as revenues.



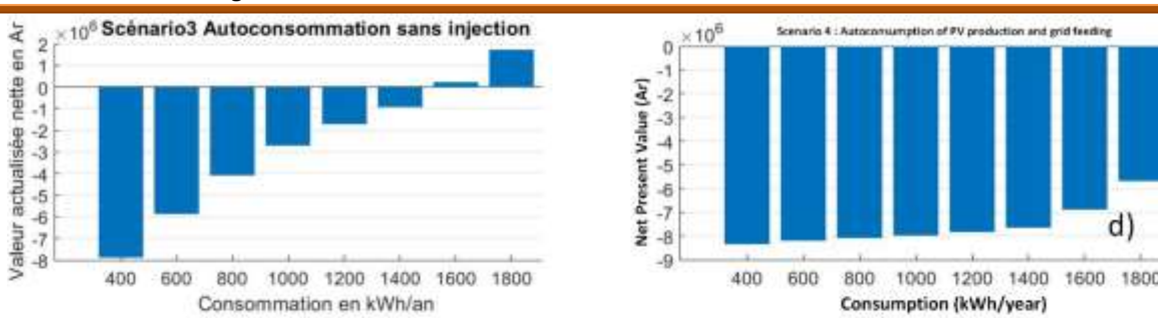


Figure 2 Variation of NPV with consumption for scenarios 1, 2, 3 and 4

5.3. Influence of the variation of the installed peak power

According to the Figure 3.a), Figure 3.b), and Figure 3.d), the profitability of scenarios 1, 2, and 4 increase as the installed capacity increases. This is explained by the fact that the increase of the installed capacity increases the self-production, and thus also the sale by injection of electricity. In contrast, for scenario 3, the curve in Figure 3.c) shows that there is an optimum to the capacity to be installed which is, in the case of our study, of 1000Wp. In fact, the more the installed power is undersized compared to the consumption, the more the part of the energy drawn from the network increases and thus decreases the NPV of the project. On the other hand, the more the installed power is oversized compared to the consumption, the more the energy injected for free increases. In this case, the oversizing only reduces the NPV by increasing the investment.

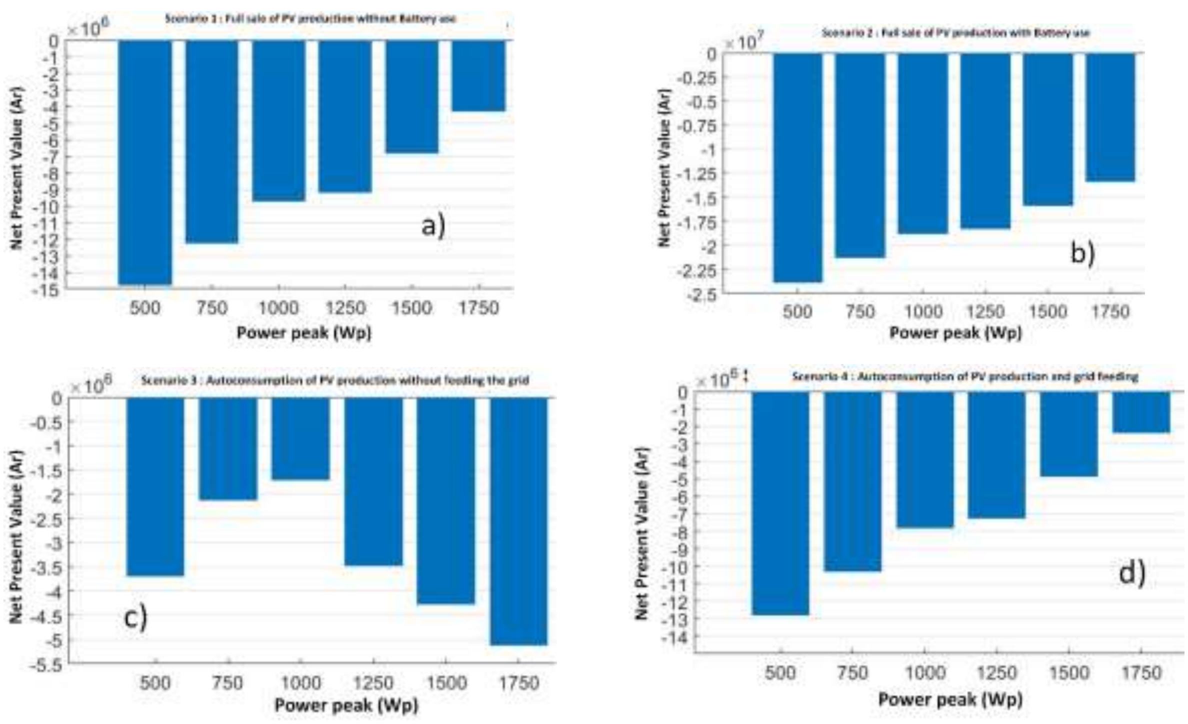


Figure 3 Variation of NPV with installed capacity for scenarios 1, 2, 3, and 4.

CONCLUSION

This study examines how factors such as injection price, electricity consumption, and installed peak power influence the profitability of residential PV installations connected to the Malagasy grid.

Our findings suggest that maximizing the sale of solar energy through direct injection, without storage, at a price of 600MGA/kWh or higher, while consistently utilizing grid-supplied electricity, can enhance profitability.

Parametric analyses indicate that increasing the injection sale price positively impacts the profitability of grid-connected PV systems. However, high consumption relative to expected levels is advantageous only for self-consumption PV setups. In contrast, excessive consumption may render projects unprofitable for installations with full injection of production.

Furthermore, undersizing installations relative to user needs hampers profitability, while oversizing is beneficial primarily in scenarios involving injection sales.

Future studies could optimize results through sensitivity analyses considering combined parameter effects. Additionally, evaluating scenarios with fluctuating electricity selling prices and exploring new setups, such as self-consumption without storage, would further enrich our understanding.

Ultimately, this research can inform the development of regulations and policies aimed at fostering the integration of residential PV systems into the Malagasy grid.

Abbreviations and Acronyms

JIRAMA : Jiro sy Rano Malagasy, Company responsible for water and electricity supply

MATLAB : Matrix Laboratory. Programmation software

NCF : net cashflow or cashflow (in French : FNT Flux Net de Trésorerie)

NPV : Net Present Value. (in French : VAN Valeur Actuelle Nette)

PVSYST : Software for sizing and simulation of photovoltaic installations

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