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Article

Impact of self-consumption and regulatory approaches on the profitability of a grid-connected PV setup plant for a net-zero-emission villa in Morocco

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Abstract: For a bioclimatic villa located in Marrakech, Morocco, electricity and bills were monitored for several years in this study. Energy was aggregated into days and months to be reconciled with monthly bills. Demand-side management, namely shifting electricity consumption to the daytime, improved the investment payback time to acceptable levels. Results are used (i) to analyze financial sensitivity to self-consumption and (ii) to compare the profitability of the actual situation of the villa in self-consumption without redemption of surpluses with other possible regulatory approaches (surplus sales and net-metering).

Keywords: net-zero-emission house; grid-connected photovoltaic plant without storage; demand-side management; technical monitoring and assessment; financial monitoring and assessment

1. Introduction

Without energy storage, the difficulty in making a domestic solar photovoltaic (PV) system profitable lies in the usually poor synchronization of electricity demand with daytime solar electricity production. An hourly load unsuitable for solar can even cancel out the advantage of being in a location with an excellent solar resource, such as this study's site in Marrakech, Morocco. For a villa located in the suburbs of Marrakech, its goal was, as written in the first brochures of the villa at the time, to offset all greenhouse gas emissions by solar compensation of energy consumption (electricity and some butane gas). The villa is bioclimatic since its construction and has become an energy research laboratory on buildings for researchers from Cadi Ayyad University, Marrakech [1–4].

Obviously, electric energy storage [5] or thermal energy storage [6] is the best solution to increase the part of solar energy locally consumed by any photovoltaic plant (self-consumption) but, at present, with high battery prices in Morocco due to import duties, an additional investment for storage is not likely to improve the profitability of installation. Because of this, the author decided to avoid storage in the present study in order to adapt the capacity to net-zero conditions and to explore the path of energy demand-side management to improve the profitability of the setup. The energy demand-side management was enabled by the fact that the villa has a large garden (4000 m^2) requiring irrigation and a swimming pool requiring water filtration, both of which can be programmed to be done during the daytime.

In Morocco, the initial version of the 2010 Law 13/09 on renewable energies did not allow the injection of electricity into the low-voltage network, but the 2016 Amendment 58/15 lifted this ban. However, a buy-back tariff for surpluses has not been defined yet by the National Electricity Regulatory Authority, created in 2016 by Law 48/15, even though it was supposed to. In the meantime, surpluses that are injected into the network are therefore lost, to the benefit of electricity distributors. The objective of the study was therefore to make as profitable as possible a solar PV system that is installed without storage, despite this unfavorable legal context forcing the injection of surpluses at a loss when operating a net-zero-emission house.

2. Photovoltaic system sizing

2.1. System sizing according to existing energy consumption and PV yield before the project

The aim for the villa since the beginning was to make a net-zero-emission home, and hence manual consumption readings were performed to size the PV system and not just to check the bills.

2.1.1. Rated PV power required to compensate greenhouse gas emission from grid electricity

Figure 1 shows the following:

- The cumulative feed from the grid (kWh) is in blue, as taken periodically from two installed utility meters for 14 years.
- The two different slopes are line adjustment for periods before and after the end of 2019 following the PV system's installation.

The graph in **Figure 1** clearly shows the different trends between the periods before and after the installation of the PV system (end of 2019). It can already be anticipated that nearly 52% energy savings ((18,706−9088) kWh/18,706 kWh) during the period from 2020 to 2024 with respect to the period from 2011 to 2019. For the period before 2019, the adjustment of cumulative consumption by a straight line (presented as a dotted blue line) shows an average slope of 18,706 kWh/day, or 6832 kWh/year (i.e., 569 kWh/month).

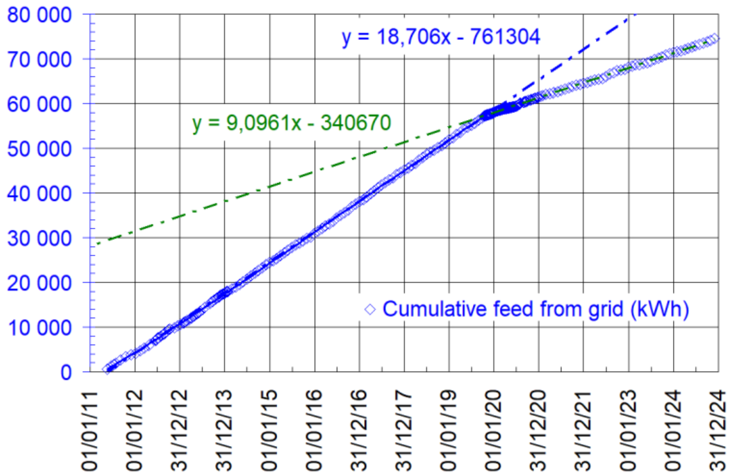


Figure 1. Cumulative electricity consumption before and after installation of PV system (end of 2019).

Considering a 95%-efficiency inverter fed by 30°-tilt polycrystalline silicon PV modules mounted facing nearly south (the building faces 17° towards the east), the long-term yearly averages of PV yields (Y_{AC} in kWh/Wp.day) from three different sources were obtained:

- From SolarMed Atlas [7]: Y_{AC} (SMD) = 1722 Wh/Wp.year.
- From the inverter manufacturer (SMA Solar Technology AG), as collected from its Sunny Portal website [8]: Y_{AC} (SMA) = 1758 Wh/Wp.year.
- From a calculation following a previous work [9]: Y_{AC} (PRP) = 1736 Wh/Wp.year

Comparing the three datasets with that of this project is somewhat outside the scope of the study. However, it can be shown that before this work, at the end of 2019, the three available data showed an average of Y_{AC} = 1739 Wh/Wp.year. The definition of yearly AC photovoltaic yield links the solar production of AC electricity, E_{sp}, to the rated power, P_R:

$$Y_{AC} = E_{sp}/P_R \quad (1)$$

Hence, the 6832 kWh/year found above would require a theoretical rated power of PR_1 = 3929 Wp of PV modules.

2.1.2. Rated PV power required to compensate greenhouse gas emissions from butane gas

Electricity carbon intensity (CI) is the mass of greenhouse gases generated per kWh of supplied electricity:

$$CI = m(CO_2)/E_{sp} \quad (2)$$

hence,

$$P_{R2} = m(CO_2)/(Y_{AC} \times CI) \quad (3)$$

Due to the dominance of coal-fired electricity in the Moroccan electricity mix, if all line losses are taken into account, each kWh saved at the exit of the National Office of Electricity and Drinking Water’s low-voltage network prevented a CI of 820 gCO_2eq of greenhouse gas emissions during the year preceding the installation of the photovoltaic system. In addition, the butane emission factor is around 3033 gCO_2eq per butane kg [10], which means that, to offset the $m(CO_2)$ = 218 $kgCO_2eq$ emissions from the annual consumption of six cylinders of butane gas of 12 kg, 266 kWh of renewable electricity must be yearly injected into the low-voltage output of the electricity network, which would require a theoretical PR_2 = 153 Wp of PV modules.

2.1.3. Final photovoltaic system sizing to compensate emissions from both electricity and butane

The total theoretical nominal power to be installed of PR = $PR_1 + PR_2$ = 4082 Wp was rounded to 4400 Wp for the installation of 16 Jinko Solar modules rated at 275 Wp each. Two rings of 8 PV modules feed two inputs for a 5kW SMA inverter. With a yield of 1739 Wh/Wp.year, these were expected to generate 7652 kWh/year of solar AC electricity, i.e., more than the 6985 kWh of power needed for net-zero emissions.

In 2018, the 6832kWh annual electricity requirement would have generated 5602 $kgCO_2eq$/year. When added to the 218 $kgCO_2eq$ from the butane gas emission, this gave a total of 5820 $kgCO_2eq$/year. Therefore, the elimination of 6275 $kgCO_2eq$ of emissions by the 7652 kWh/year of planned solar electricity consumption should achieve the objective of net-zero emissions, while even offering a margin for a possible increase in energy consumption.

2.1.4. Technical details of installation

Figure 2 shows how the photovoltaic modules act as the input of the synchronous inverter, which itself feeds the internal electric grid of the villa. An SMA smart meter was placed between the villa's general connection box and the distributor's meter to measure the energy coming from the electricity network. In **Figure 2**, the solid-line arrows show the possible directions of electricity flows, while the dotted lines show the information network connections. The smart meter not only separately measures the input or output of electricity but also collects inverter data and provides commands to reduce solar electricity production to a given level when the option is enabled.

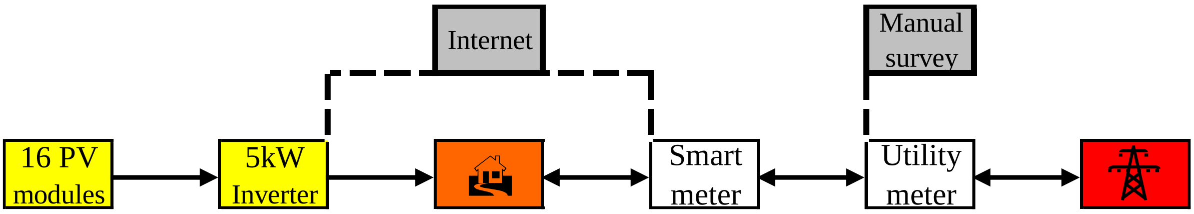


Figure 2. Simplified diagram of the installation, its measuring instruments and information system.

2.2. Data acquisition system

In the data acquisition system, the smart meter collects the measured solar electricity production (E_{sp}) from the inverter and measures both the feed from the grid (E_{fg}) and the surplus injection into the grid (E_{ig}) from its included bidirectional meter. Electric power is measured in 5s increments before being averaged and stored with a 15-min time interval until the end of March 2024, after which it was lowered to a 5-min interval [11]. All average powers are subsequently integrated to obtain daily, monthly or yearly energy yields.

To ensure the best possible coincidence with the energy readings of the distributor's energy meter located on the street, which were taken as a reference, the energy data were all adjusted by a multiplicative factor of 99.935%, as obtained via the least squares method of 55 monthly manual readings of the feed from the grid on the distributor's energy meter by counting more than 15000 cumulative kWh.

In **Figure 3**, each one of the basic data items is characterized by four different datasets: its designation and symbol followed by its key performance index and the economic revenue that it could possibly generate.

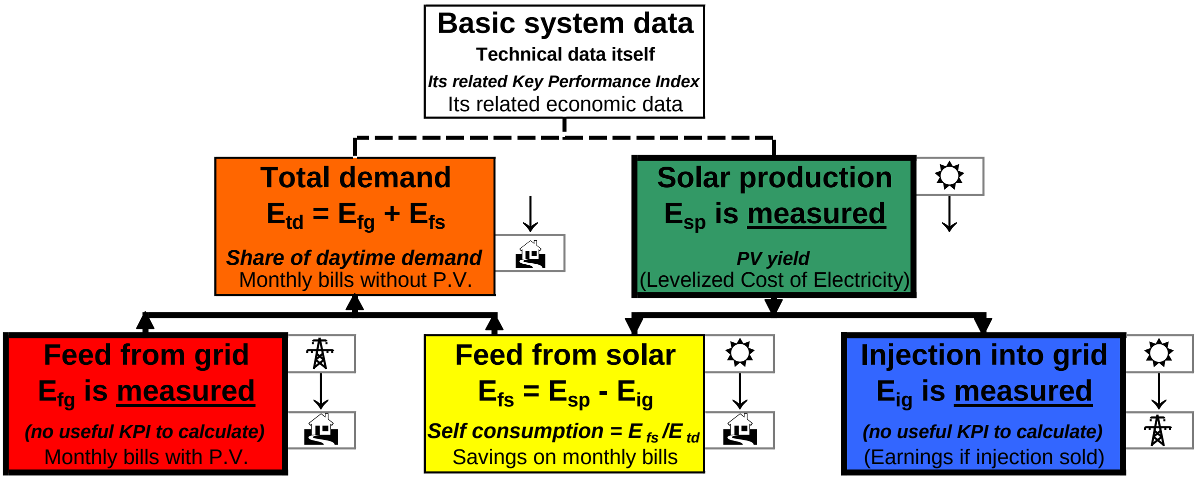


Figure 3. System basic data, their related key performance index and economic data (arrows show energy flow directions).

The feed from the solar PV system, E_{fs}, is obtained by subtracting the injection into the grid, E_{ig}, from solar electricity production, E_{sp}. The total demand, E_{td}, is obtained by adding the feeds from the grid, E_{fg}, and the solar PV system, E_{fs}.

The feed from the solar PV system (E_{fs}) appears as a "bridge" shared by the total demand (E_{td}) and the local solar electricity production (E_{sp}), and the combination of E_{fs} (yellow box) results in:

- The total demand, E_{td}, (orange box) when combined with the feed from the grid (E_{fg} (red box).
- Solar electricity production, E_{sp}, (green box) when combined with the injection into the grid, E_{fg} (blue box).

Through careful daily collection of data between 22 October, 2019, and 30 November, 2024, a database was created consisting of approximately 200,000 instantaneous average power data points, which were subsequently integrated for each of the 1869 days and then aggregated into monthly and annual energy figures. However, for unidentified reasons, some data from the smart meter were unable to be collected for a total of 59 days, namely, 18 days between 17 November and 5 December, 2021, where all data were missing, and 41 days between 1 April and 11 May, 2024, where only the demand data were missing. The missing data were replaced with those of equivalent days from another year. Missing data due to electric grid failure, however, were not replaced in order to obtain a realistic dataset.

2.3. Characteristics of actual or hypothetical phases studied

From the beginning of April 2011 to 16 February 2020 (3241 days), the electricity supply contract for the villa was prepaid. This contract required the use of a digital meter (called "Noor"), which counts the absolute value of the power passing through it for billing the electricity injected into the network. This meter (labeled as Meter A) prevents the construction of a net-zero-energy villa. Hence, for the solar PV system's installation, an inverter was required in order to put into a mode of restriction of electricity injection into the network. A total of 3241 days of this supply contract were subdivided into three unequal phases:

- A long preliminary phase (3113 days), named Phase A1, made it possible to define the existing needs used for sizing the system. In addition, Phase A1 served as a reference to measure the savings gained from the installation of the PV system.
- A very short subsequent phase (14 days), named Phase A2, was used to approximately estimate, with the new digital metering, what happened when a nighttime irrigation system was programmed following the solar PV system's installation.
- A short phase (114 days), named Phase A3, allowed the understanding of the impact of switching the programming of the irrigation system to a daytime schedule during the waiting time for the distributor to change the supply contract and the meter in order for the project to achieve the net-zero-emission target during Phase B.

During Phase B, electricity injection into the grid was ignored by the newly installed analog meter because of the meter's anti-return wheel. Phase B lasted for 1746 days at the writing of this paper.

Referring to Phase A1 (without the installation of the solar PV system), five scenarios were constructed for the financial study:

- Three scenarios were constructed on the basis of a 20-year continuation of Phases A2, A3 and B.
- A hypothetical fourth scenario was built on the basis of a 20-year continuation of the energy data from Phase B but with a future purchase of surplus energy at 0.45 Dh/kWh (1 Dh ≈ 0.1 US$).
- Another hypothetical fifth hypothetical scenario used the same hypotheses but with a net-metering approach.

Table 1 summarizes all the conditions for each phase described above.

Table 1. Different phases and hypothetical cases treated in this study.

Counter	Supply contract	Surplus sales (Dh**/kWh)	Phase	Irrigation Period	PV (kW)	Injection into grid	Date started	Date ended	Duration (days)
"Noor"	Prepayment	0.00	A1	Night	0	No PV	01/04/11	09/10/19	3113
			A2	Night	4.40	Restricted	10/10/19	24/10/19	14
			A3	Day	4.40	Restricted	24/10/19	15/02/20	114
Analog	Post-payment	0.00	B	Day	4.40	Allowed	16/02/20	27/11/24	1746
Smart	Surplus sales*	0.45	C	Day	4.40	Allowed	With future sales of surplus		
	Net-metering*	In kind	D	Day	4.40	Allowed	Hypothetical case		

* Hypothetical cases; ** 1 Dh = 1 MAD = 1 Moroccan Dirham ≈ 0.1 US$.

Obviously, the injection of electricity into the grid was restricted during Phases A2 and A3 to avoid having to pay for it.

For the hypothetical case of surplus sales, which still does not yet exist in Morocco (Phase C), the price was set up at the rounded value of 0.45 Dh, just 0.10 above the Levelized Cost of Energy at 0.35 Dh for an investment of 40,000 Dh, a 2%/year depreciation and a −0.7%/year production loss. Just for reference, distributors buy daytime electricity at 0.85 Dh/kWh.

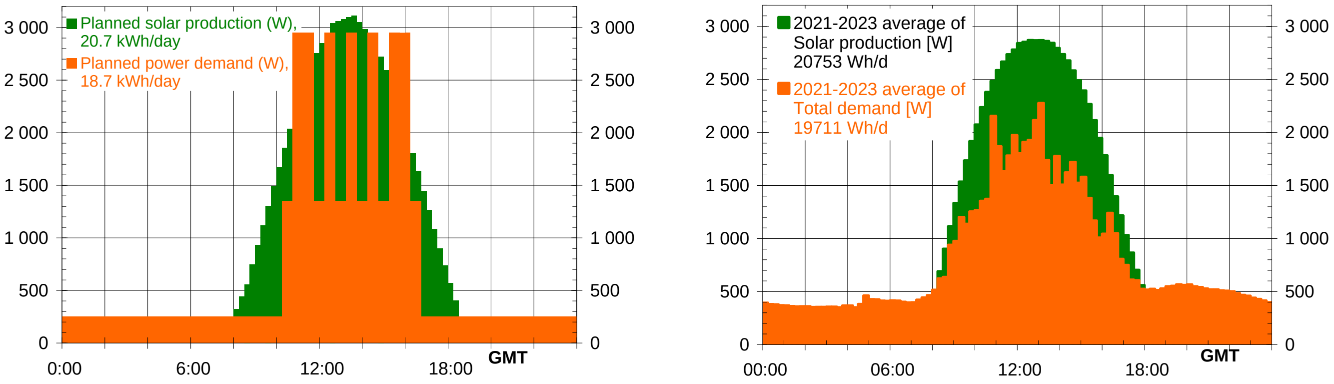
2.4. Details of demand-side management (for phases A3 and B)

For a short period in 2019, preliminary approximate sub-metering measurements made it possible to determine the following segmentation of electricity consumption:

- 37% was used for pumping well water using a 2700W pump supplying programmable irrigation via eight different solenoid valves, to which eight half-hour periods of irrigation were assigned.
- 23% was used filtering the swimming pool water using a 1500W pump, whose operation was programmed at 15-min periods.
- The remaining 40% was used by the house. In order not to change the habits of its occupants, it was decided not to manage the demand by appliances. This is why it was already known in 2019 that reaching a 60% self-consumption level would be difficult.

To allow some form of synchronization with the direct production of solar electricity (depicted as the green histogram in **Figure 4a**), the demand for the garden (irrigation and filtration) programming is shown by the orange histogram in **Figure 4a**:

- The half-an-hour activation of the eight solenoid valves triggers the drip irrigation of the garden (vegetable garden, fruit trees, ornamental plants and lawn) via a well pump with a 2.7kW power demand.
- The swimming pool filtration pump has a 1.5kW power demand.
- The base of the histogram represents the consumption of the house, assumed to be constant at 0.25 kW. The total daily consumption therefore approaches the 18.7 kWh defined in **Figure 1**.



(a) **(b)**

Figure 4. (a) Predicted load curve of the villa; **(b)** three-year average of total demand in reality.

The difference between the programming and reality (orange histograms in **Figure 4**) is explained by several reasons:

- The simplest explanation is that the nighttime consumption of the house turns out to be higher than expected.
- Opening the irrigation solenoid valves results in the intermittent operation of the well pump due to the hysteretic control of the pressure tank–pressure switch system (which cuts at 3 bars and restarts at 2 bars).
- Some or all of the solenoid valves can be closed due to the plants' irrigation cycle

or rain, respectively, when some or all parts of the garden no longer need to be irrigated.

- Finally, various reasons required the short or prolonged shutdown of the pool water filtration.

Figure 4b allows the calculation of an average self-consumption of 55% (11,025/(11,025−8983)) during the period from 2021 to 2024. This same self-consumption value is found later in Subsection 3.1.4.

2.5. Financial hypotheses: Rates, investment and depreciation

There cannot be a realistic financial study adapted to a country (e.g., Morocco) without actual electricity prices. The low-voltage ones are listed in **Table 2**. They have not been changed since August 2017, which was the end of the latest program contract between the Moroccan government and the National Office of Electricity and Drinking Water.

Table 2. Low-voltage electricity fares in Morocco since August 2017.

Supply contract	**Fixed fees (Dh*/m)**	**Monthly (kWh/m)**	**Price (Dh) per consumption segment (kWh/m)**					
			≤ 100	**≤ 150**	**≤ 210**	**≤ 300**	**≤ 500**	**∞**
Prepayment	0.00	> 0	1.5407					
Postpayment	62.65 for 4kW subscription	≤ 100	0.9010	NA				
		≤ 150	0.9010	1.0732	NA			
		≤ 210	1.0732			NA		
		≤ 300	1.1676				NA	
		≤ 500	1.3817					NA
		> 500	1.5958					

* 1 Dh/m = 1 MAD/month = 1 Moroccan Dirham/month ≈ 0.1 US$/month.

Table 2 shows that the prepayment contract (using Meter A) is simple, which is without fixed fees and with a flat 1.5407 Dh/kWh for a subscribed power of 6 kW. For postpayment (Phase B and using Meter B), the fixed monthly fee was set at 62.65 Dh/month for the villa’s 4kW subscription. Social and environmental reasons are behind the tiered pricing system, which is as follows:

- Below 150 kWh/month, customers pay:
    - 0.9010 Dh/kWh for the first 100 kWh.
    - 1.0752 Dh/kWh for the following 50 kWh.
- Higher consumptions are treated as follows:
    - For more than 500 kWh/month: 1.5958 Dh/kWh.
    - For consumptions below or equal to 500 kWh/month: 1.3817 Dh/kWh from 0 to 500 kWh.
    - For consumptions below or equal to 300 kWh/month: 1.1676 Dh/kWh from 0 to 300 kWh.
    - For consumptions below or equal to 210 kWh/month: 1.0732 Dh/kWh from 0 to 210 kWh.

Phase B rates also allow appreciating the billing non-linearity resulting from the non-flat kWh price.

For each of the five scenarios, all financial simulations (payback time and net present value) considered the following:

- An investment of 40,000 Dh (rounded) for the PV plant.
- A project duration of 20 years and a discount rate of 2%/year (tax-free popular savings for deposits at the Morocco Postal Bank).

3. Results and discussion

3.1. Phase B: Results of technical monitoring and assessment

Sections 3.1 and 3.2 will only refer to Phase B not only because it is the longest phase and the present phase but also because, as already said, Phase A and its numeric utility counter charges for electricity injection and makes the net-zero-emission project non-profitable.

3.1.1. Phase B: Effective achievement of net-zero-emission goal

At the beginning of 2020 and at the end of 2024, the data for the days of a few weeks missing during Phase B were supplemented with average days of the year in order to complete the data for all years. **Figure 5** shows the evolution of the yearly technical data of the villa, which revealed the following:

- A total demand of 7304 kWh/year, as fed from the solar PV system (4030 kWh/year) and from the grid (3284 kWh/year).
- Solar electricity production of 7714 kWh/year, among which 3691 kWh/year were injected into the grid.

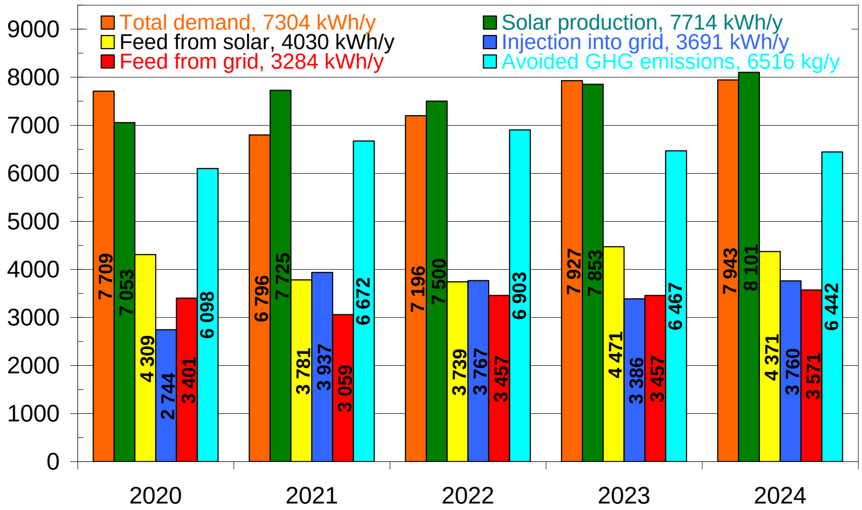
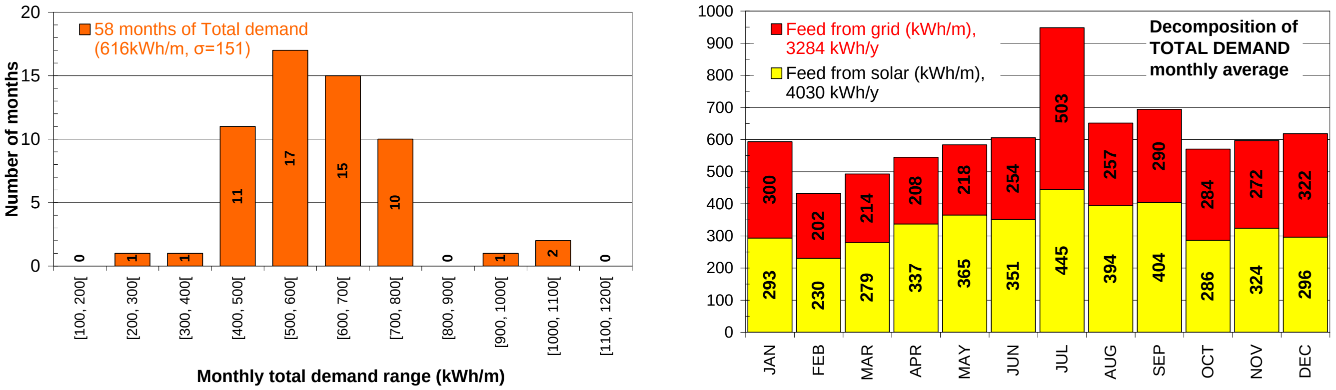


Figure 5. Evolution of yearly cumulative technical data (2020–2024).

As there is still no GHG emissions data available from the Ministry of Energy after 2021 [12], the carbon intensity of Moroccan electricity delivered in low voltage was calculated from (i) emission intensities of electricity from fossil sources [13] and (ii) electricity production data in [14], which also made it possible for calculating the efficiency of the network. The calculations found that the solar electricity production offset an average of 6515 kg of CO_2 equivalent per year. From **Figure 5**, it can be confirmed that, with more than 6275 kg avoided, the goal of net-zero emissions has been achieved.

3.1.2. Phase B: Monthly total demand and its fluctuations



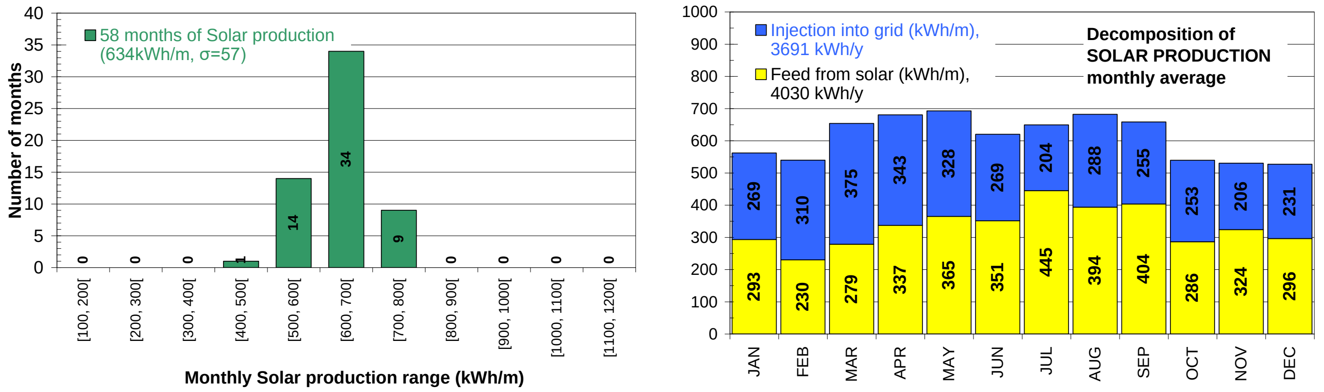
(a) **(b)**

Figure 6. (a) Distribution of monthly total demands; **(b)** monthly averages over four full years.

Figure 6 shows that, at 151 kWh/month, the standard deviation of the monthly total demand for electricity lies around 25% of the average at 616 kWh/month. The fluctuation is driven by seasonal factors, such as the following:

- In February, irrigation is minimal and there is no need for heating the bioclimatic house.
- In July, an excess of consumption is caused by air conditioning from three earth-air heat exchangers [1,2]. The house is usually empty in August.

3.1.3. Phase B: Monthly solar electricity production and its fluctuations



(a) **(b)**

Figure 7. (a) Distribution of monthly solar electricity productions; **(b)** monthly averages over four full years.

Figure 7 shows that, at 57 kWh/month, the standard deviation of solar electricity production lies around 9% of the average at 634 kWh/month. The fluctuation is driven by the main seasonal extremes:

- The maxima for months near the equinoxes, for which the 30° tilt angle is optimal.
- The minima during the five months surrounding the winter solstice between October and February.

3.1.4. Phase B: Monthly self-consumption and its fluctuations

Self-consumption is given by the ratio of the feed from the solar PV system to the total demand, as given in **Figure 3**. **Figure 8** shows that, at 6.5%, the standard deviation of the self-consumption lies around 12% of the average at 55%. The self-consumption fluctuation is driven by the main seasonal extremes:

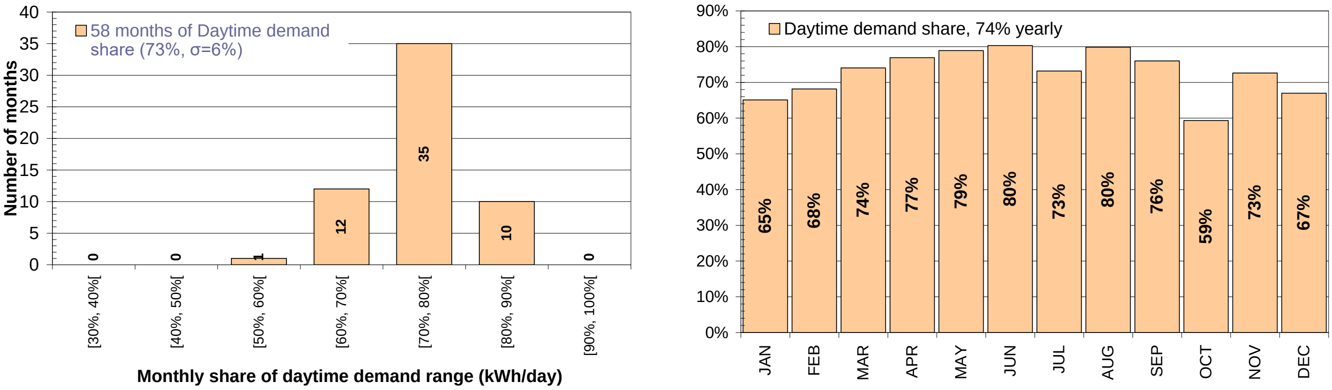
- The maxima where there is more solar electricity.
- The minima for the month of July, when total demand is exceptionally high.

(a) **(b)**

Figure 8. (a) Distribution of self-consumptions; **(b)** monthly averages over four full years.

3.1.5. Phase B: Monthly daytime total demand share and its fluctuations

From sunrise to sunset each day, the total daytime demand (in kWh/day) was calculated and divided by the total 24-h demand (in kWh/day) to obtain the total daytime demand share. This was done because, obviously, the increase in daytime consumption improves the rate of self-consumption, which in turn has a favorable impact on the financial performance of the investment.



(a) **(b)**

Figure 9. (a) Distribution of monthly daytime demand shares; **(b)** monthly averages over four full years.

Figure 9 shows that, at 6%, the standard deviation of the total daytime demand share is about 8% of the average at 73%. The self-consumption fluctuation is driven by the same aforementioned periods.

3.1.6. Phase B: Self-consumption rate—Nexus of total daytime demand share

The share of daytime electricity demand plays an essential role in improving the self-consumption rate, which is a key factor for the profitability of a photovoltaic system for self-consumption and even more so for those that do not use storage. **Figure 10** shows the correlation between monthly self-consumption and the related share of daytime total demand. The bisector, separated by the red line, indicates that self-consumption is lower than the daytime total demand share simply because it is only a part of the total demand.

Figure 10 suggests that, for cases such as this villa, monthly self-consumption reaches 75% of the monthly daytime total demand.

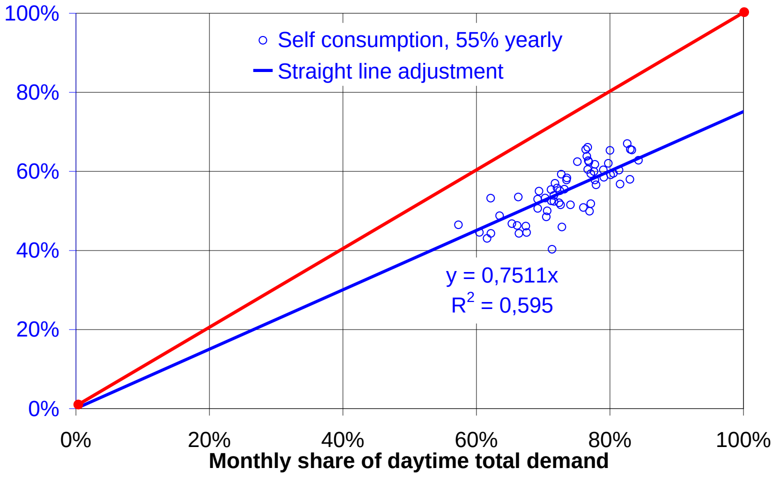
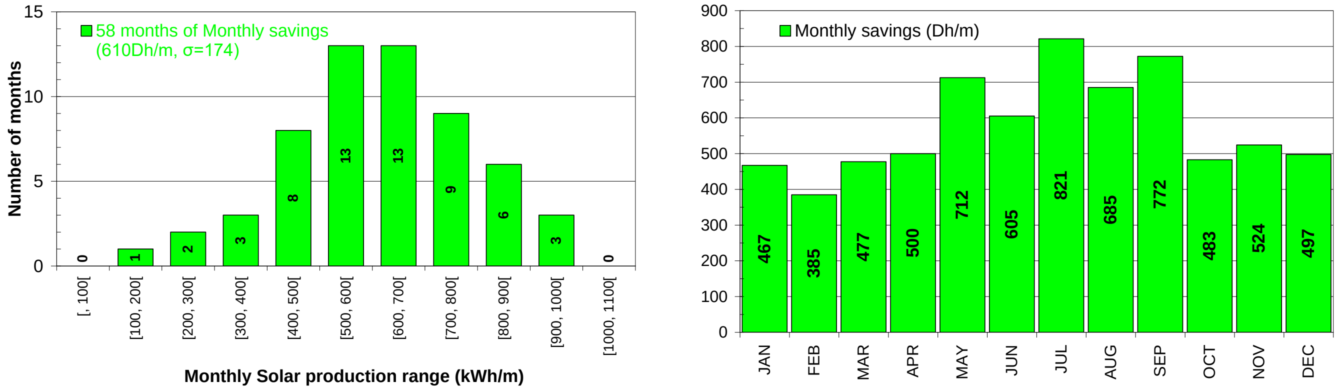


Figure 10. Self-consumption rate against share of daytime total demand.

3.2. Phase B: Results of financial monitoring and assessment

3.2.1. Phase B: Monthly savings and fluctuations



(a) **(b)**

Figure 11. (a) Distribution of monthly savings; **(b)** monthly averages over four full years.

Figure 11 shows that, at 174 Dh/month, the standard deviation of the monthly savings is about 29% of the average at 610 kWh/month. The fluctuation is driven by seasonal factors, as follows:

- The five “summer” months (May to September).

- The remaining “winter” months.

3.2.2. Phase B: Evolution of cumulative savings towards payback time

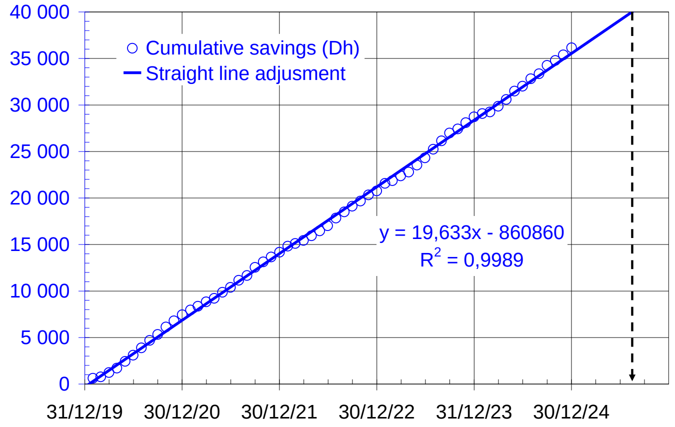


Figure 12. Evolution of cumulative savings towards investment value (40,000 Dh).

Figure 12 shows the growth, at the end of each month during Phase B, of cumulative savings and their evolution towards the payback date (31 August 2025), which should occur 67 months after operation (almost 5.6 years). This figure will serve as a reference to keep a critical eye on future values obtained by the extrapolation of monthly averages and not by using the real values of each month.

3.2.3. Phase B: Payback time and net present value versus self-consumption

Keeping the investment at 40,000 Dh and savings of 610 Dh per month due to the PV system, as obtained from **Figure 11a**, and with fares from **Table 2** for the self-consumption rate to reach 100%, **Figure 13** shows the following:

- 20-year net present values (NPVs) at a 2% yearly depreciation rate (green histogram and left scale).
- Payback time (red line and right scale).

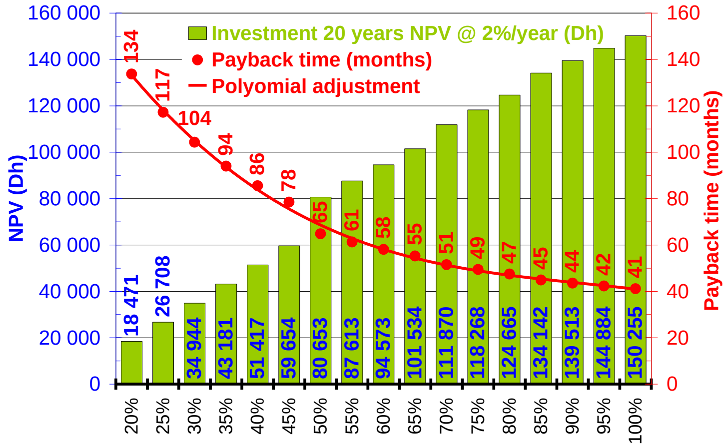


Figure 13. Sensitivity of NPV (left scale) and payback time (right scale) to self-consumption in Phase B.

The 61 months of payback time obtained at 55% of self-consumption is not the same as the 67 months obtained in **Figure 12**, where the non-linearity of the bills was accounted for, while the calculations for **Figure 13** did not.

This graph is valid for almost every country, provided that all financial hypotheses are fulfilled (investment, depreciation, and electric energy prices), which tacitly means it is valid for Morocco. In this case, the payback time remains transposable as it is but the NPVs must be adapted to the installed power (4.4 kW).

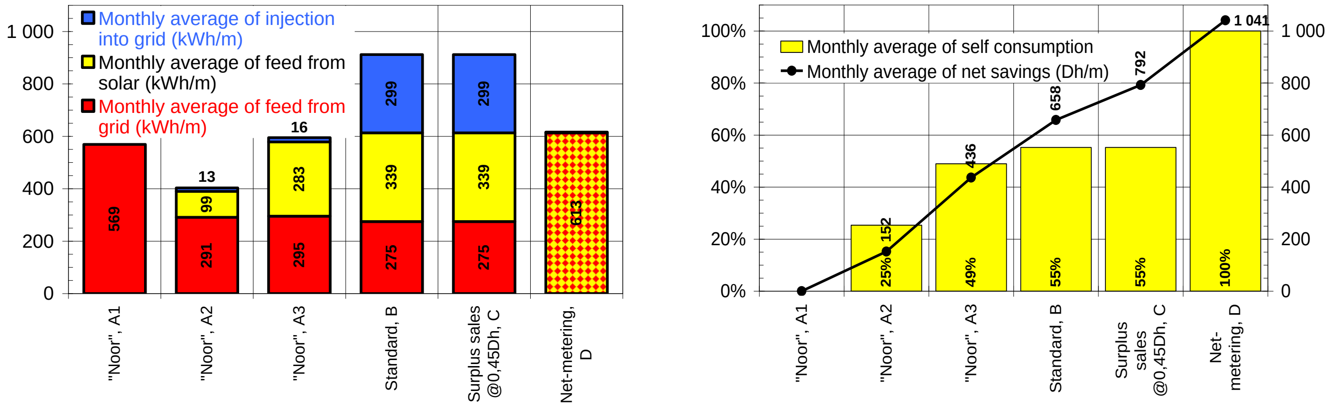
3.3. Long-term financial projections of all phases (A1, A2, A3, B, C and D)

3.3.1. Hypotheses for simulations of long-term financial projection

For the simulations of the long-term financial projection of each phase, monthly averages were used and assumed to be maintained beyond their term for 20 years.

Figure 14 shows the different hypotheses that were considered in the simulations of the long-term financial projections of the four real-world phases (A1, A2, A3 and B) and the two hypothetical situations (Phase C for the sale of surpluses and Phase D for using the net-metering approach):

- **Figure 14a** shows the monthly averages of total demands, broken down into the following:
  - The feed from the grid (red);
  - The feed from solar electricity production (yellow);
  - The amount of solar electricity production injected into the grid (blue).
- **Figure 14b** shows the resulting monthly averages of the following:
  - Self-consumption (yellow histogram and left scale), as deduced from **Figure 14a**.
  - Net savings (black line and right scale), which included the sales for Phase C and calculated using the energy data from **Figure 14a** and fares from **Table 2**.



(a) **(b)**

Figure 14. Hypotheses considered in simulations of long-term financial projection for each case: **(a)** initial monthly technical hypotheses; **(b)** monthly savings deduced from each self-consumption.

3.3.2. Simulations of long-term financial projection of all six cases (A1, A2, A3, B, C and D)

Based on the hypotheses shown in **Figure 14** for each of the four real-world phases (A1, A2, A3 and B) and the two hypothetical situations (C and D), **Figure 15** shows the NPV (green histogram) of the 40,000Dh investment for 20 years, taking into account a 2% yearly depreciation rate and the payback time (red line).

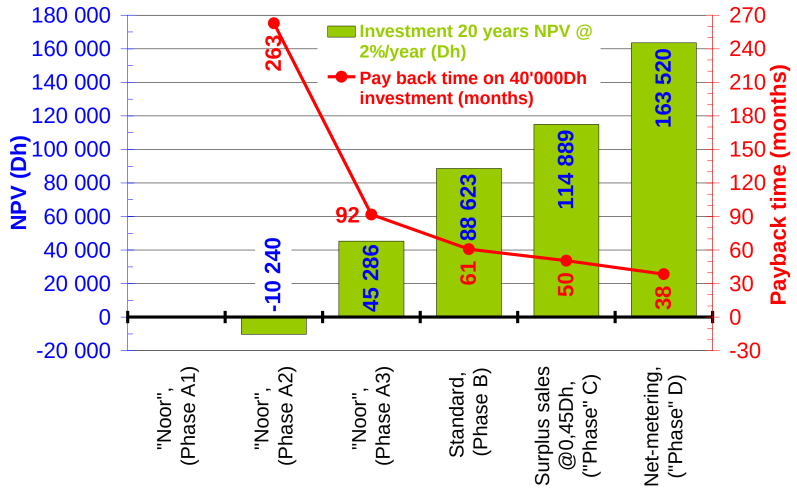


Figure 15. NPV (left scale) and payback time (right scale) for Phases A1, A2, A3, B, C and D.

By increasing the daytime consumption rate, the use of demand-side management on its own allowed the following:

- Making the NPV positive.
- Reducing the return-on-investment time to less than 10 years.

Even if the same self-consumptions are found in **Figure 13**, the results of the financial analysis may not be the same because the rates are not the same in prepayment (A) as in postpayment (B). It is the case, for instance, for the very short Phase A3, for which **Figure 14b** shows a self-consumption rate of 49% and **Figure 15** shows a 92-month payback, while the payback time for a 50% self-consumption rate obtained from **Figure 13** is 65 months.

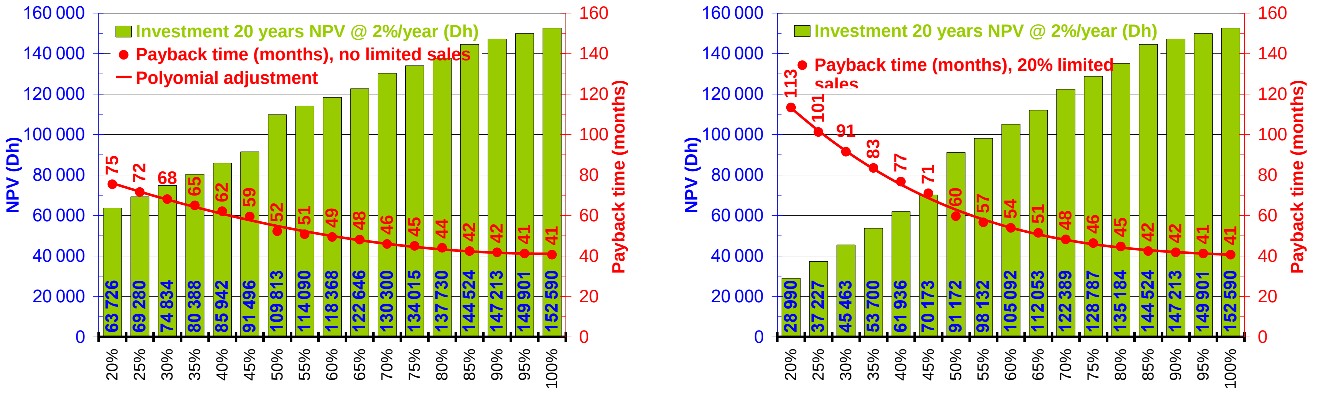
Even though the values are near each other, the payback time obtained in **Figure 12** (67 months) is not exactly the same as the one obtained here for Phase B (61 months) because the former takes into account the month-by-month non-linearity of the bills instead of the average. Despite all this, the general trends in the results remain consistent with each other.

3.3.3. Hypothetical Phase C (surplus sales): Payback time and NPV versus self-consumption

In this subsection, as presented in **Figure 16**, for the hypothetical Phase C, the same sensitivity of NPV and payback time to self-consumption as in Subsection 3.2.3 (**Figure 13**) but with two different scenarios:

- A distributor will buy all the energy surpluses from a self-producer (as supposed above for C).
- The distributor limits its purchases to 20% of the self-producer (as provided for

in the new Self-Production Law, with which the author fully disagrees).



(a) **(b)**

Figure 16. Sensitivity of NPV (left scale) and payback time (right scale) to self-consumption in two scenarios of Phase C: **(a)** without limit of surplus sales; **(b)** with limit of surplus sales at 20%.

At 100% self-consumption, the two scenarios match perfectly but, because of the slower decrease, the following observations are revealed:

- To reach 5 years of payback time, the first scenario, as shown in **Figure 16a**, needs only 40%–45% of self-consumption, while the second, as shown in **Figure 16b**, needs 50%–55% of self-consumption,
- It is just hopeless to have profitable investments with less than 30% of self-consumption.

In the second scenario, as shown in **Figure 16b**, a project that does have a zero-emission goal and strives to avoid system oversizing (excess of investment) has to set a target of 80% self-consumption (and 20% injection), which very difficult to achieve in a house without storage and without demand-side management flexibilities.

4. Discussion

All theoretical financial studies were carried out with real-world data and working hypotheses that are actually valid for Morocco. During Phase B, only 59 days among 1746 of the data were lost (3.3%), which granted overall reliability to the study’s technical figures and their calculated fluctuations and averages. Extraction and comments of the technical data and results were limited to whatever was useful for the financial analysis.

More than 70 scientific articles on grid-connected PV systems in Morocco were reviewed and even if all of them collected the same type of data, all were based on 100% self-consumption and, moreover, none made the same technical-economic calculations that were made here. In addition, the attempt to make a habitat or a professional building with net-zero emissions was not addressed in these works, much less making it profitable.

In a future study by the author, the maps of solar PV payback time for different daytime-demand shares in Morocco will be drawn.

5. Conclusion

The achievements of the experimental part are as follows:

- Sizing the system with the use of existing yearly AC productivity was sufficient to obtain results compatible with expectations.
- The daytime programming of irrigation and swimming pool water filtration made it possible to increase the share of daytime demand from 36% to 74%, which in turn increased the self-consumption coefficient from 25% to 55%, opening the possibility of an acceptable payback time between 61 (calculated) and 67 months (actual) and potential 20-year NPVs bigger than twice the initial investment.

The conclusions from the simulations of the long-term financial projections are as follows:

- On one hand, the self-consumption sensitivity study gave a minimum payback time of 41 months, which allows the NPV to be multiplied by 8 when self-consumption increases from 20% to 100%.
- On the other hand, the simulation of the six cases showed that the sale of surpluses at 0.45 Dh/kWh should reduce the payback time by around 20% (from 61 to 50 months), while the net-metering approach reduces it to 38 months—very close to that of the simulated self-consumption at 100%, which gave 41 months.

To achieve buildings, offices or factories with net-zero GHG emissions, it is easy from the technical point of view to calculate and implement grid-connected PV plants without storage. However, if their economic performance is excellent under a hypothetical net-metering regime, under other regimes, profitability strongly depends on the self-consumption ratio. Designing net-zero-emission buildings with a grid-connected PV setup alone is shown to be almost impossible when there is no flexibility to increase daytime consumption.

Despite this, it can be concluded that acceptable profitability is allocated to the net-zero-emission villa in Morocco by reaching 55% self-consumption through better demand-side management. However, while this is possible in the villa with its very large garden, it is very likely that increasing the share of daytime consumption is not easy to extrapolate for other types of housing. Consequently, making a net-zero-emission home profitable cannot be done either by refraining from buying back excess self-produced electricity, as is currently the case, or by limiting the shares bought back, as provided for in the new Self-Production Law. The next law on self-production should provide for a repurchase of injected electricity limited to 20% of production but the price is not yet unavailable.

Conflict of interest: The author declares no conflict of interest.

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