Optimal Design and Control of Stand-Alone Photovoltaic System and Analyzing their Environmental and Techno-Economic Aspects in Tunisia: Case Study of Borj Cedria.

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Abstract- This research work explores the economic, technical, and environmental aspects of Stand-Alone Photovoltaic Systems (SAPS) for off-grid electrification in the area of Tunisia (a case study of Borj Cedria). Optimal design and control for this system are also presented. PVSYST software and the PV-GIS site are utilized to assess environmental and technical analysis. To analyze the SAPS installation cost, a design office was consulted to estimate the equipment cost.
Then, a nonlinear Sliding Mode Controller (SMC) is performed in this paper to extract the maximum power from photovoltaic systems (PVs) under different climatic conditions. This control is based on the Perturb & Observe (P&O) Maximum Power Point Tracking (MPPT) method. The control diagram presented with the photovoltaic system is simulated under MATLAB - SIMULINK. The environmental results found the benefits of optimal configuration PV/Batteries adopted in terms of the CO_2 emissions reductions of up to 66.24 kg/year. Furthermore, the economic results of this work might help the Tunisian government develop effective planning and policies to provide affordable as well as reliable electrification to off-grid regions.
Moreover, the SMC simulation results are compared to classical proportional integral control (PI) while keeping the same weather changes and system parameters. Simulation results with real data prove the proposed approach.

Keywords Techno-economic aspects, environmental aspects, off-grid electrification, stand-alone photovoltaic system design, nonlinear sliding mode control.

1. Introduction

Actually, Tunisia faces several electrical crises, such as low-output power outages and insufficient supplies. The electricity network serves most off-grid areas because it requires long transmission lines at a high cost.

To resolve this issue, many alternative solutions are proposed, such as the integration of renewable energy systems. The growth of green energy systems such as photovoltaic system (PV) and wind energy converter systems (WECS) has exceeded the most optimistic estimations for supplying loads in rural and remote regions [1]. A photovoltaic system (PV) is one of the optimal solutions. It is identified as a clean energy resource, helpful for greenhouse effect mitigation, and a promising alternative for electrifying autonomous sites. On the other hand, Tunisia's climate is favorable to solar energy use. It is located in North Africa, bordering the Mediterranean Sea. This location is attractive for photovoltaic applications.

Furthermore, off-grid PV systems are considered a good energy solution for electrifying remote and rural Tunisian sites because of their ease of transport, maintenance, and installation.

However, it is also found that many small, isolated sites in Tunisia rely on diesel generators as a back-up element for electricity. Given the high running costs of these generators in terms of transportation costs and fuel availability, a battery storage system is considered as an interesting back-up element.

Nevertheless, before installing autonomous PVs in these regions, it is necessary to evaluate its technical and economic feasibility.

In the literature, multiple studies are reported on renewable energy systems and microgrids for remote and rural electrification [2].

Several studies have addressed relevant background and information about their project, particular the sizing, design, environmental, technical, and economic assessments of their proposed power supply systems [2][3].

For that, different software has been used by researchers, such as MAT-Lab/Simulink, HOMER Pro, RETScreen, and OPAL-RT. Some papers are briefly discussed in this article.

For example, Muhammad Irfan et al. [3] performed a techno-economic investigation of an autonomous PV in Punjab province situated at Pakistan while developing mathamatical equations and accessing the NASA database. Whereas, Al-Qahdan et al. [5] discussed the off-grid PV design integrating battery storage for the Malaysia University building and then evaluated its technical performance via PVsyst simulation.

More recently, A. El-Shafy et al. [6] looked at SAPS Design and Economic Analysis to Electrify a Household in a Remote Area in Egypt. In this paper, an analysis of the life cycle cost (LCC) is performed to assess the economic viability of the system.

On the other hand, A. Saleh Aziz et al. [7] accomplish the optimum design of an off-grid connected solar power system at Iraq. The Matlab module in HOMER is performed to improve the allocation strategy, taking into account both techno-economic and environmental perspectives.

Then, H.M. Ridha et al. [8] proposed a SAPS optimum design in Malysia based on the optimization of the multi-purpose of particle swarm. This method is implemented using MATLAB software.

After that, M.N. Uddin et al. [9] investigated the environmental and techno-economic feasibility of solar mini-grids in Bangladesh to serve 2500 households using MATLAB and HOMER software.

This paper deals with SAPS techno-economic and environmental assessments for the Tunisian off-grid area.

In this study, PVsyst simulation and PV-GIS site are utilized for environmental and technical performance evaluation of the proposed SAPS. MATLAB software is used to simulate model and control electric power system.

Therefore, Borj Cedria (the northeast area of Tunisia) is selected, and its techno-economic and environmental aspects are evaluated in this study. To assess this region’s solar energy potential, a systematic approach was developed.

Firstly, solar radiation received on a horizontal surface is evaluated.

Then, the optimum tilt angle is calculated to optimize PV production in the corresponding region.

In fact, the Borj Cedria region has region has wide solar potential suitable for the production of electricity. Concurrently, by varying the angle of solar photovoltaic to the optimum tilt angle, the power generation can be increased considerably.

In this context, researchers have presented several methods to calculate the optimum angle of inclination.

For example, Liu Z et al. [10] used the Hay model to calculate the optimum tilt angle of a grid-connected fixed photovoltaic system. Whereas Yang J. et al. [11] evaluated a computer-aided design to calculate the optimum.

More recently, Li F. et al. [12] presented the optimum tilt angle on an inclined plane and the overall amount of solar irradiance under varying azimuth. On the other hand, Wang B et al. [13] proposed the optimum inclination angle of solar components, considering resources.

Compared with these methods, our study aims to provide a robust and very simple method for PV based on real electrical measurements (I-V) and to compare this optimum PV system with a real PV system developed in our previous work [14].

This work uses PVSYST simulation software for the PV system design. The global solar radiation, depending on the latitude and position of the sun, is determined from PV-GIS. The optimal tilt angle is calculated through PVSYST software.

Assumptions for the design and analysis processes and their impact on the validity of the results

• It assesses the off-grid PV energy configuration that can supply the expected load profile in the Borj Cedria area as a typical peri-urban site.

• It implements a “framework for stand-alone photovoltaic system design” and assesses its performance in a developing region.

• It provides a comprehensive feasibility study that considers technical, environmental, and economic aspects to determine the optimal and practical energy solution for the selected site.

• It can inform energy system planners, policymakers, energy investors, and other researchers on the technical, environmental, and economic conditions necessary to electrify a peri-urban area using photovoltaic energy systems.

A paper outline is as follows:

The materials and methods of this research work are exposed in the next section.

PV system configuration, technical study, data collection, and electrical load demand are exposed.

In this section, Borj Cedria is proposed as an example to determine the optimum angle of inclination via PV-SYST. PV-GIS is introduced to estimate the global solar radiation because of the latitude and position of the sun.

Section 3 presents SAPS (stand-alone photovoltaic system) environmental and techno-economic results for the northeast area of Tunisia. Photovoltaic panels characteristics are verified via MATLAB/Simulink simulations. The required SMC strategy for different climatic conditions is illustrated. Following this is the discussion of the results. Finally, the conclusion and prospects are presented in Section 4.

2. Materials and methods

2.1. Case Study Background

We conducted the study in Borj Cedria, northeast Tunisia, between January and December 2022.

The SAPS configuration is depicted in Fig. 1. It is installed in the LPV laboratory at Technopark Borj Cedria. It allows for the supply of residential loads in remote and off-grid regions. It consists of solar panels; a regulator, batteries, and a DC load. The photovoltaic function consists of converting sunlight into direct electric current. The controller monitors the electrical input from the solar panels and controls the amount of battery charging and discharging.

The surplus DC power is accumulated in the battery when PV power is available. This stored energy may be consumed later, when PV power is unavailable or when demand is high.

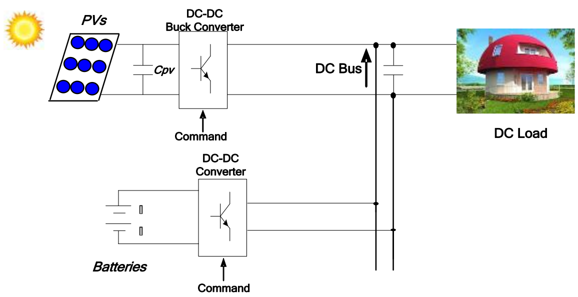

Fig. 1. Stand-alone PV system.

2.2. Technical study and data collection

2.2.1. Site assessment methodology

- *Prepare an appropriate site.*

The choice of the appropriate PV system's site is a priority for optimal exploitation of solar resources. Several criteria must be satisfied to determine the optimum location of a PV system, such as the wide availability of solar radiation and the possibility of foreseeing its temporal and spatial distribution [1].

Borj Cedria is used as a case study site to perform our estimate of the PV potential. Tunisia is a relatively small country in northern Africa, bordering the Mediterranean Sea. The Borj Cedria region is located in the Tunisian northeast at near 36.71 latitude and 10.42 longitude, according to the PVGIS site (Fig. 2).

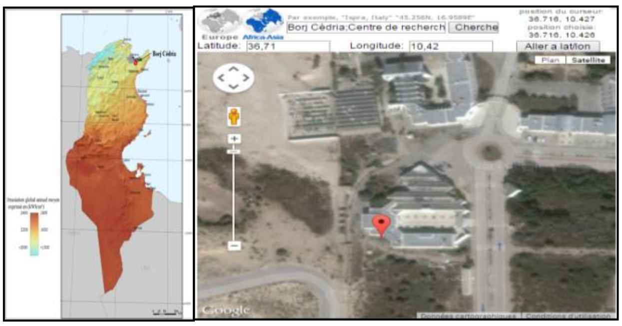

Fig. 2. Borj Cedria's site location (PVGis interface).

- *Prepare meteorological data site*

To predict the SAPS performance in a location, it is required to collect meteorological data from the site under discussion from PVGis and Weather underground sites.

The average monthly data of solar radiation incident on a horizontal surface and temperature at the site under consideration are depicted in Fig. 3. We note that the incident solar energy is very high, particularly during the summer months, where it exceeds 8kWh/m^2 per day on horizontal. It is clear that July has a significant global radiation and August has a very high average temperature.

Fig. 3 shows that even in winter, Borj Cedria enjoys a month of sunshine. The solar energy incident exceeds 2.5 kWh/m^2 per day in December and January.

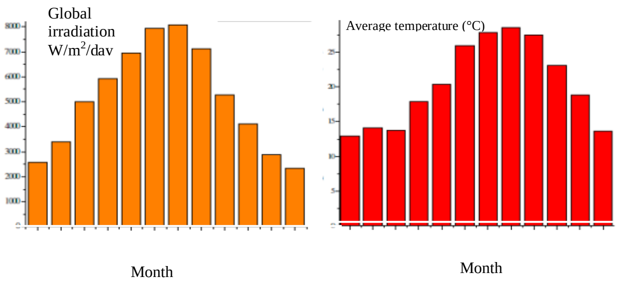

Fig. 3. Monthly global radiation and temperatures (°C) in 2022 for the Borj Cedria site (PVGis, Weather Underground interfaces).

These data collected from PVGis are inserted in the PVsyst (the interface below) to create the site under discussion and carry out the next step (Fig. 4).

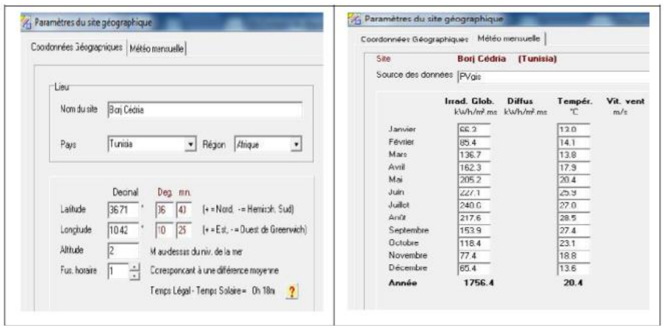

Fig. 4. Geographical and meteorological coordinates' interface (PVsyst software).

Preliminary studies have shown that the Borj Cedria site has huge energy potential. Consequently, we conclude that any future PV system installation on the same site could be very profitable (Fig. 3 and Table 1).

2.2.2. Optimum tilt angle change in Borj Cedria

Table 1 presents, respectively, global solar irradiance, direct horizontal irradiance and diffuse irradiance followed by the optimum tilt angle in Borj cedria. In fact, these data are obtained from of the PVGIS site and PVsyst interface monthly measurements.

These data (Table 1) illustrate that the solar radiation incident on a surface is related to its angle and orientation. For example, the solar radiation data takes its average in July and reaches a maximal value of 8W/m^2 per day for global solar radiation. Furthermore, the extreme diffuse solar radiation is 7W/m^2 /day during the same month.

The optimal tilt angle in Borj Cedria varies between 3° and 63°; the minimum optimum tilt angle is 3° (June) and the maximum is 63° (December), as mentioned in Table 1.

Therefore, these two radiance ratios (Diffuse/Global) as a function of atmospheric conditions affect the optimum tilt angle and radiance slope.

In addition, for a surface at a specific location, increasing its optimum angle results in more radiation being received during the winter than during the summer.

Table 1. Monthly change of direct horizontal irradiance, global solar irradiance, and diffuse irradiance at the Borj Cedria site (PVGis interface)

Monthly Average Temperature (°C) in 2022 (Weather Underground interface)

Month	H	HT	Optimal inclination (degree)	(D / G)	Average temperature (°C)
Jan	2590	4110	60	0.41	12,96
Feb	3410	4780	52	0.40	14,10
March	5010	6090	40	0.40	13,80
April	5920	6310	26	0.33	17,9
May	6960	6690	12	0.31	20,38
June	7930	7200	3	0.24	25,9
July	8080	7530	7	0.21	27,80
August	7140	7300	19	0.22	28,54
Sept	5290	6160	35	0.32	27,43
Oct	4120	5510	48	0.38	23,06
Nov	2870	4470	59	0.37	18,8
Dec	2330	3900	63	0.40	13,61
Year		70080	35	0.31	-

With H: radiation on a horizontal plane (Wh/m²/day), HT: radiation on a plane with optimum inclination (Wh/m²/day), (D/G):Proportion between diffuse irradiation and global.

For solar applications that need power from solar panels primarily during the winter, the optimal angle must be large. Whereas when solar panels are utilized in the summer, the inclination must be small. To maximize energy availability in the winter, summer, and all year round, the optimal tilt angle should be calculated.

2.2.3. Optimal tilt angle determination

The tilt angle is defined as the module inclination angle measured with respect to the horizontal.

The optimum tilt angle should maximize the overall solar radiance received by the generator surface for one year. Therefore, determining this optimum requires information on the annual global solar radiance received at any angle between 0° (horizontal position) and 90° (vertical position) and the selection of the maximum power point.

Furthermore, different regions have different optimum angles for PV panels.

To determine the optimum tilt angle of our site under discussion, a simulation result on PVsyst was made with the orientation and inclination of the PV panel (Fig. 5).

Since the considered area is situated at 36.71 north latitude and 10.42 east longitude.

The simulation result shows that PV panel orientation is to the south (azimuth of 0°) with an inclination of 32, so that the PV benefits from the maximum irradiation available during the period of use.

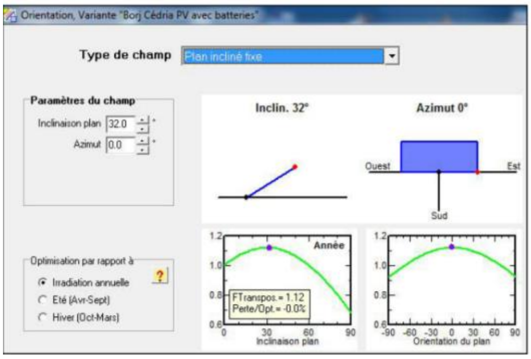

Fig. 5. PV panel azimuth and tilt optimization (PVGIS, PVsyst interfaces).

2.3. Demand of Electrical Load

The SAPS in the remote region of Borj Cedria is supposed to be modest and not require huge amounts of electrical power devices. Electrical loads composed of lighting (fluorescent lamps), whose daily electrical demand during a typical day is exposed in Fig. 6 and Table 2.

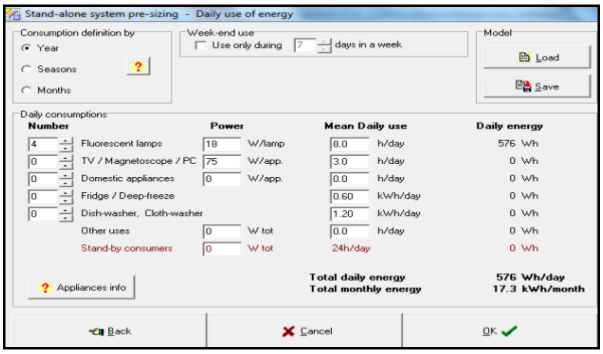

Fig. 6. Daily average load demand from PVsyst Interface.

Table 2. The SAPS Load Data from PVsyst

DC Load	Number of units	Power (W) / Unit used	Functioning hours / Day	Wh/day
Lights	4	18	8	576Wh/j
Total				**210240 Wh/year**

The average daily load demand can be calculated from PVsyst, as shown in Fig. 6 and Table 2, as 576 Wh/day. It is supposed that this load demand is constant throughout the year.

2.4. Environmental Analysis

The updated Tunisian Nationally Determined Contribution (NDC) is committed to reducing its carbon intensity by around 45% by 2030. Mitigation efforts mainly focus on the energy sector, which accounts for 75% of the proposed emission reduction. The building sector is one of the country's principal polluters; it accounts for 27% of its total energy consumption. As a solution, renewable energy projects for buildings can contribute to improving environmental impacts, such as awakening communities about climate change and carbon dioxide gas reduction. An environmental impact assessment (EIA) presents a process for predicting the environmental effects of project development, then decreasing human footprints and maximizing the positive effects [15]. It can be carried out in several aspects, of which two main ones are identified: air pollution and water pollution. In fact, the proper use of renewable energy sources can alleviate air pollution and the greenhouse effect [16]. In this study, in terms of energy savings and GHG emissions, we focus on the environmental impacts of stand-alone photovoltaic systems (SAPS). In order to calculate the SAPS GHG emissions, the average annual energy production (EP) was multiplied by its CO_2 equivalent (EC), as mentioned in equation (1).

$$GHG = EC \times EP \quad (1)$$

2.5. Economic Analysis

In order to make green energy sources more appealing to Tunisian citizens with limited income, this study developed the profitability of investments in an autonomous PV project via an economic study. To examine PVs financial viability, the researchers adopted in the literature three main traditional valuation approaches: to mention payback period (PBP), net present value (NPV),and returns on investments (ROIs) [15].

In this project, the economic tool adopted is the ROI, defined by calculating.

The ROI presents one of the measures of financial performance that is utilized to assess both capital investment and operation efficiency or to compare the efficiency of several investment projects. In this study, ROI measures autonomous solar system revenue against initial operational investment and the cost of maintenance. To calculate ROI, the benefit or return on investment is divided by the investment cost, as described in equation (2):

$$Roi = \frac{\sum_{i=1}^{T} R_t - i}{i} \quad (2)$$

Where t is the valuation period, R is the annual net cash flow, i is the investment cost for the PV system, and T is the PV technical lifetime.

As to R, the annual cash flow of each technology equals the marginal revenue minus the marginal cost. For all economic assessments, the investment cost is the capital one of the solar system and its installation.

2.6. Nonlinear sliding mode controller

Nonlinear Sliding Mode Controller (SMC) was used for SAPS. Several advantages were offered by this method, such as minimum output current distortion, robustness against parameter variations, and excellent reference tracking. The SMC design is presented in the next section [15] and [16].

2.6.1. Nonlinear sliding mode controller (SMC) design

- *PV system modeling*

A simple single-diode equivalent electrical model is adopted. The equivalent circuit of a photovoltaic cell has a diode connected in parallel, a current source (I_{pv}), parallel resistor (R_p), and series resistor (R_s) [16]. The equation that reflects the relationship between current and voltage in the PV module can be expressed as follows:

$$I_{PV} = I_{ph} - Is\left[\exp\left(\frac{V+I.Rs}{V_T}\right) - 1\right] - \frac{V+I.Rs}{Rsh} \quad (3)$$

- *Buck converter modeling*

The buck converter model (Fig. 1) is obtained using the fundamental laws that govern the system's operation. The converter dynamic equation (4) can be written as follows:

$$\begin{cases} \frac{dx_1}{dt} = \frac{u}{L}X_2 - \frac{V_{DC}}{L} \\ \frac{dx_2}{dt} = \frac{1}{R_{PV}\,C_{pv}}X_2 - \frac{u}{C_{pv}}X_1 \end{cases} \quad (4)$$

Where $X = [X_1\ X_2]^T = [I_L\ V_{PV}]^T$, $R_{PV} = \frac{V_{PV}}{I_{PV}}$ presents the equivalent load connected to the PV, V_{DC} is the buck converter voltage, L is the buck converter inductance, C_{PV} is the panel capacitor, and u is duty cycle.

- *Sliding mode controller design :*

Equation (4) can be described as:

$$\dot{x} = f(X) + g(X)d + H \quad (5)$$

Where

$$f(x) = \begin{pmatrix} 0 \\ \frac{X_2}{R_{PV}\,C_{pv}} \end{pmatrix}, g(x) = \begin{pmatrix} \frac{X_2}{L} \\ \frac{-X_1}{C_{pv}} \end{pmatrix}, \text{ Then } H(x) = \begin{pmatrix} -\frac{V_{DC}}{L} \\ 0 \end{pmatrix} \quad (6)$$

According to the PV system modeling, the expression of the maximum power point MPP expression is described as follows :

$$\frac{\partial\, VP_{PV}}{\partial\, V_{PV}} = \frac{\partial\,(I_{PV}\ V_{PV})}{\partial\, V_{PV}} = \frac{\partial\, I_{PV}}{\partial\, V_{PV}}\, V_{PV} + I_{PV} = 0 \quad (7)$$

This expression is selected as the slip surface for the SMC MPPT

$$S(x) = \frac{\partial\, P_{PV}}{\partial\, V_{PV}} \quad (8)$$

In the analysis of the relationships between operating point position on Fig. 7 and S(x) state, it is necessary to make the following order law choice:

$$u=\begin{cases}0 & \text{if } S(x) \geq 0 \\ 1 & \text{if } S(x) < 0\end{cases} \quad (9)$$

2.6.2. Nonlinear sliding mode controller MPPT algorithm

In this section, the design of a sliding mode controller (SMC) utilizing a reference voltage given by an MPPT algorithm will be demonstrated. For this command, the sliding surface becomes:

$$S(x)=x_2-V_{pvref} \quad (10)$$

Where $V_{pv\text{-}ref}$ is the voltage given by the MPPT (Perturb & Observe) algorithm. The command law for this case is provided by:

$$u=\begin{cases}0 & \text{if } S(x) < 0 \\ 1 & \text{if } S(x) > 0\end{cases} \quad (11)$$

- *Maximum power reference voltage*

The role of the MPPT algorithm is to determine the optimum PV output voltage chosen, $V_{pv\text{-}ref}$, which allows the PVs to operate at their MPP. For this, the Perturb & Observe algorithm integrating adaptive stepping is presented.

- *Adaptive P&O algorithm*

The Adaptive Perturb & Observe algorithm flow chart is illustrated (Fig. 7).
The adopted algorithm (adaptive Perturb & Observe) is characterized thus:

$$\begin{cases}V_{pvref}(t)=V_{pvref}(t-h)+K_1 sign\left(\dfrac{\Delta P_{pv}}{\Delta V_{pv}}\right) \\ \Delta V_{pv}=V_{pv}(t)-V_{pv}(t-h) \\ \Delta P_{pv}=P_{pv}(t)-P_{pv}(t-h) \\ K_1=K_2\left|\Delta P_{pv}\right|\end{cases} \quad (12)$$

Where K_1 is the adaptive step dependent on the change in PV power, h is the step time, and k_2 is the positive constant gain, adjusted to get the best MPPT operation.

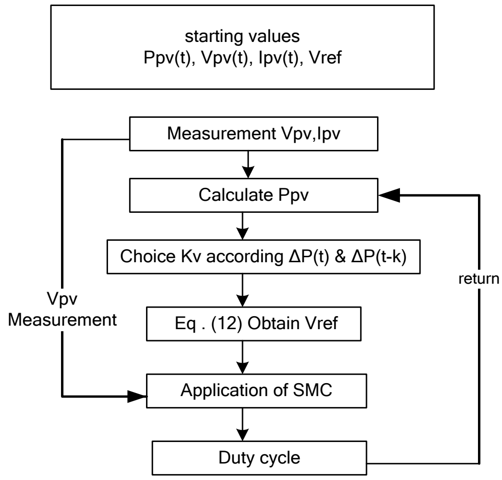

Fig. 7. Algorithm flow chart of adaptive P&O.

3. Results and Discussion

3.1. Environmental Impact Analysis

An environmental study is based on PV's ecological impact. Therefore, the ecological impact in terms of cell pollution is certainly minimal but still present. According to various calculations, we estimate an emission of 540 g of CO_2 for the production of 1 kWh by the Tunisian Company of Electricity and Gas STEG, so with photovoltaics, we save 0.46 kg of CO_2 for each kWh. Thus, with our 144 kWh/year installation (as described in previous section 2.2.2: 70080 kWh/m^2/year multiplied by panel surface of 2.05 m^2), we will avoid 66.24 kg of CO_2 per year.

3.2. Economic Study

After a technical study, we propose to estimate the PV installation cost. It is a question of financially evaluating the equipment price and overall cost of this project.
To find the installation cost, the overall cost of the equipment we need is estimated. These costs are related to the installation size, which depends on the equipment's power and brands.
The table below (Table 3) shows the different costs of equipment pieces in the PV installation. It indicates that our stand-alone PV installation costs 916.416 DT. We note that 1 euro equals to 3,34 Tunisian dinars.

3.2.1. Economic profitability

During this project's economic study, all financial values are evaluated for 25 years from its creation by calculating the return on investment. These results are presented in a table and diagram as shown in Table 4 and Fig. 8, respectively. The results obtained are cited:

- The installed power is equal to 0.1 kWp.
- The electricity tariff is equal to 0.156 DT/kWh.
- STEG's annual inflation rate is equal to 7%.

The table below summarizes the entire economic profitability study of our installation.

Table 3. PV installation estimated cost

Solar component	Quantity	Unit price (DT)	Total price	VAT rate	VAT price (DT)
Module	2	81,000	162,000	18,00%	29,160
Battery	1	350,000	350,000	0,00%	350,000
Regulator	1	90,000	90,000	18,00%	16,200
Module support	1	90,000	90,000	0,00%	90,000
DC cables	10	2,500	25,000	0,00%	25,000
Installation costs/Transport and assembly	1	150,000	150,000	0,00%	150,000
Total amount excluding tax			867,000		
Total VAT in TND					660,360
Total including tax to be paid by the customer in (DT)					1527,360
Grant	40%	610,944			
Self-financing					916,416

Table 4. Consumption cost assessment for 25 years

Year	kWh price (TD)	Energy production kWh/year	Energy cost (DT)	Investment cost	Fee accrual	Return of investment ROI
1	0,184	129,6	23,857	916,416	916,416	-892,559
2	0,197	129,6	25,527	0,000	916,416	-890,889
3	0,211	129,6	27,314	0,000	916,416	-889,102
4	0,226	129,6	29,226	0,000	916,416	-887,190
5	0,241	129,6	31,271	400,000	1316,416	-1685,145
6	0,258	129,6	33,460	0,000	1316,416	-1282,956
7	0,276	129,6	35,803	0,000	1316,416	-1280,613
8	0,296	129,6	38,309	0,000	1316,416	-1278,107
9	0,316	129,6	40,990	0,000	1316,416	-1275,426
10	0,338	129,6	43,860	400,000	1716,416	-2072,556
11	0,362	129,6	46,930	0,000	1716,416	-1669,486
12	0,387	129,6	50,215	0,000	1716,416	-1666,201
13	0,415	129,6	53,730	0,000	1716,416	-1662,686
14	0,444	129,6	57,491	0,000	1716,416	-1658,925
15	0,475	129,6	61,515	400,000	2116,416	-2454,901
16	0,508	129,6	65,822	0,000	2116,416	-2050,594
17	0,543	129,6	70,429	0,000	2116,416	-2045,987
18	0,581	129,6	75,359	0,000	2116,416	-2041,057
19	0,622	129,6	80,634	0,000	2116,416	-2035,782
20	0,666	129,6	86,279	400,000	2516,416	-2830,137
21	0,712	129,6	92,318	0,000	2516,416	-2424,098
22	0,762	129,6	98,780	0,000	2516,416	-2417,636

23	0,816	129,6	105,695	0,000	2516,416	-2410,721
24	0,873	129,6	113,094	0,000	2516,416	-2403,322
25	0,934	129,6	121,010	400,000	2916,416	-3195,406

According to the economic profitability calculations, we notice that the project is not economically profitable due to PV technology expenditures and the modest subsidy. Hence, the descriptive histogram of cumulative results (Fig. 8) informs us that the start of the project takes place after 88 years from the project's creation.

Therefore, the Tunisian government should design clean energy subsidies to deliver greater benefits to society.
This is achieved by assessing optimal subsidies that account for technological progress and consumer behavior.

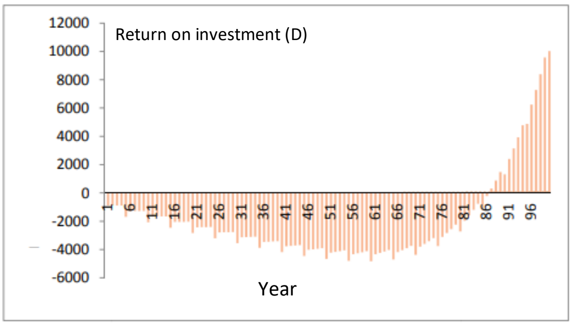

Fig. 8. The return on investment assessment depends on the year.

3.2.2. Recommandations

The next policy recommendations in Tunisia are proposed for the rapid deployment of an off-grid photovoltaic electrification program. Search results prove that the Borj Cedria region has huge potential for solar energy for electricity production. Thus, relevant authorities must develop effective strategies and take the initiative to launch a solar off-grid plan.

Other major obstacles are the unavailability of government grants and bank loans to purchase photovoltaic systems. Therefore, the Tunisian government must provide subsidies and set up micro-finance projects with low bank interest rates to encourage people in remote areas to purchase off-grid solar solutions. It is necessary to decrease the initial investment in PV systems that Tunisian residents in remote areas can comfortably purchase and install photovoltaic systems.

3.3. PV System Results

3.3.1. Experimental setup description

This experimental setup is presented in Fig. 10 and is installed within the LPV Laboratory that is located at the Center for Research and Energy Technologies, Technopark Borj Cedria. The proposed system is carried out to identify the solar panel and cell electrical characteristics, utilizing real data generated from photovoltaic modules. It allows the supply of residential loads in remote and off-grid areas. A detailed diagram describing the different instrumentation of the experimental test bench is presented in Figs. 9, 10, and 11.

The proposed experimental setup evaluation is performed for stand-alone PVs and contains the following main blocks (Fig. 10): a PV generator (type Eurosolare M 510 A), a pyranometer sensor type « Solarex », a thermocouple (LM035 probe), a controller-charger, a battery, an acquisition chain type « Multimeter/Switch System Integra series Model 2750 », an electronic loads, and a computer.

The PV module is made up of monocrystalline solar cells. It is composed of 36 cells connected in series and gathered into four sub-strings of 9 solar cells each. This module is equipped with four bypass diodes; each is mounted in anti-parallel in order to protect a photovoltaic sub-string.
PV systems are further interconnected in a two PV parallels, as shown in PVsyst interface (Fig. 11), which nevertheless supply the same output voltage at double current.

The PV panel orientation installed at the LPV Laboratory is to the south (azimuth of 0°) with an inclination of 32°, as studied above. Its major parameters are mentioned at Table 5 under the Standard Test Condition (STC) (1000 W/m2, 25°C light spectrum air mass AM of 1, 5) with the following electrical specifications data: ISC (Short Circuit Current), VOC (Open Circuit Voltage), PMPP (Maximum Power Point), IMPP (Optimal Current at Maximum Power Point) and VMPP (Optimal Voltage at Maximum Power Point).

In this test, I-V curves are obtained using a variable load (BK PRECISION 8510 600 W Programmable DC Electronic Load), which affords data from VOC to ISC for each I-V curve sufficient to sweep the I-V curve of the module under study.

The Solarex pyranometer sensor serves to measure the solar radiance captured by the PV module surface. Then, an LM035 probe glued to the rear face of the PV module is employed to measure the temperature. A data acquisition system equipped with a computer for data supervision and visualization using LABVIEW®. Economical light sources, such as 23W compact fluorescent lamp, can be useful as electrical loads.

Table 5. PV module specifications at STC (1000 W/m^2, 25°C)

Panel Type	Eurosolare M 510 A
Maximum Power	50 W
Optimal Current	2.95 A
Optimal Voltage	17 V
Short Circuit Current	3.25 A
Open Circuit Voltage	21.4 V

Fig.9. Experimental setup at the LPV laboratory.

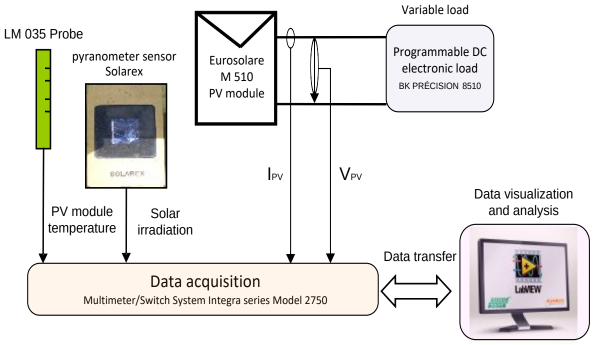

Fig.10. Experimental setup diagram.

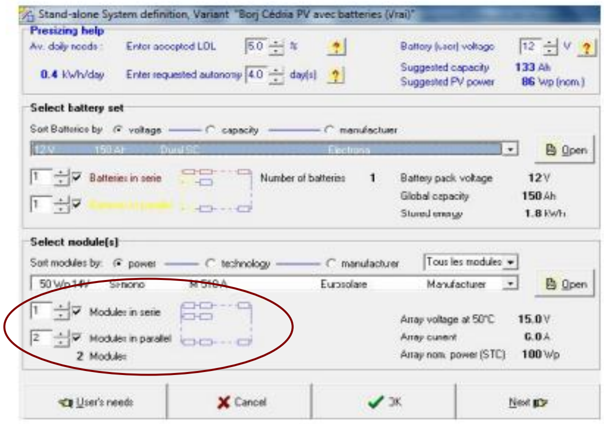

Fig.11. PVsyst interface for PV system sizing.

3.3.2. Experimental results

Experimental results are analyzed on the experimental test bench.

Fig. 12 presents the current-voltage (I-V) and power-voltage (P-V) characteristics of the Eurosolare M 510 A panel at a temperature and an incident solar radiation varying from 23ºC to 32ºC and 400 W/m^2 to 1100 W/m^2, respectively. Experimental (I-V) and (P-V) curves are measured four times, as mentioned in Table 6.

The measurements are carried out on four different days with variable conditions referring to the solar radiation and the temperature.

It is obvious that the short-circuit current of a PV module is proportional to solar radiation. It generates less current, and thus less power, when it receives a low level of radiation. It can be observed in Fig. 12 that the PV open circuit Voltage depends on temperature. It provides less voltage when it receives high temperatures.

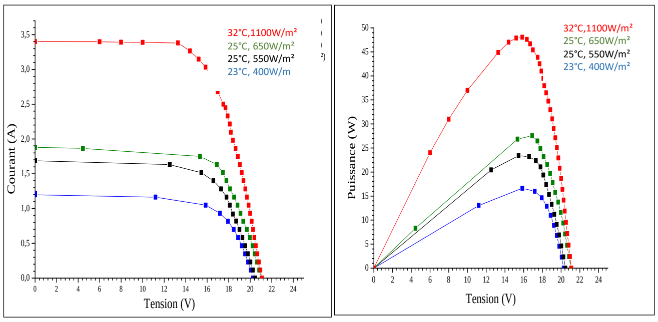

Fig.12. Experimental PV module I-V and P-V curves at variable radiation.

Table 6. Experimental data: I-V and P-V Tests

Test 1	32°C	1100W/m²
Test 2	25°C	650W/m²
Test 3	25°C	550W/m²
Test 4	23°C	400W/m²

Simulated (I-V) and (P-V) curves of the PV generator are obtained as exposed in Fig. 13. Simulation results are performed under MATLAB/SIMULINK to compare experimental one.

It is found that experimental results are consistent strongly agree with simulation results.

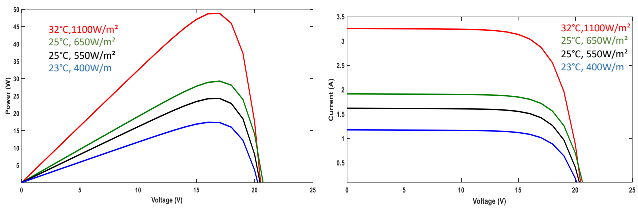

Fig.13. Simulated PV characteristics (I-V and P-V curves) under variable radiation and temperature.

This test bench allows us to compare this optimum PV system with a real PV system developed in our previous work [14]. It was revealed that there was an electrical energy reduction in the SAPS of 9% in comparison to the optimum SAPS. In fact, at 745W/m^2, the optimum PV system power is 41.5W and about 37.5W for a real PV system [14].

3.3.3. Simulation results

Simulation results are performed under solar radiation from 500 w/m2 to 900 w/m2 for a PV generator composed of two Eurosolare M 510 A panels connected in parallel.

Then, the simulation results of the SMC proposed control scheme are compared with those of the classical proportional integral (PI) control scheme.

- *Response with Proportional Integral (PI) control*

To show the performance of the proposed SMC controller, a comparison with a cascade PI controller is carried out. This control is composed of two regulation loops: The outer voltage loop and the inner current loop, as mentioned in Fig. 14.

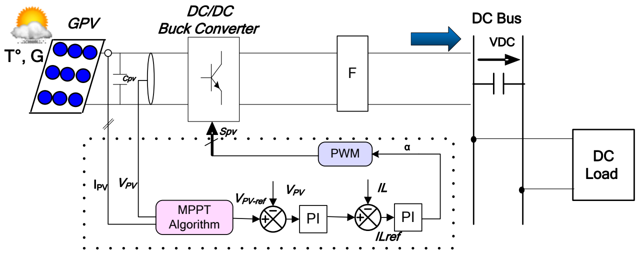

Fig.14. Control scheme with cascade proportional integral (PI).

The PI controller response built on the P and O MPPT algorithm is illustrated in Fig. 15. Fig. 15 (a–c) exposes the SMC control performance founded on the P & O algorithm under variable irradiance.

The external PI controller voltage tracking is seen in Fig. 15a. The PI controller successfully tracks the reference peak supply voltage V_{ref} generated by P & O-MPPT. VPV follows the desired set point V_{ref} within a stabilization time of 1.85 s with high ripples and an oscillation of 0.2 V; the same for the PV current supplied by P & O-MPPT (see Fig. 15b).

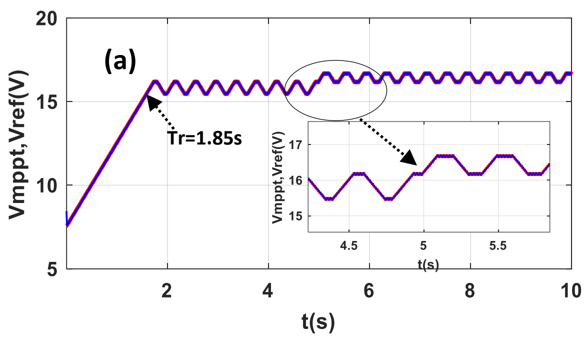

Fig.15a The proposed cascade PI controller response **(a)** PV panel voltage.

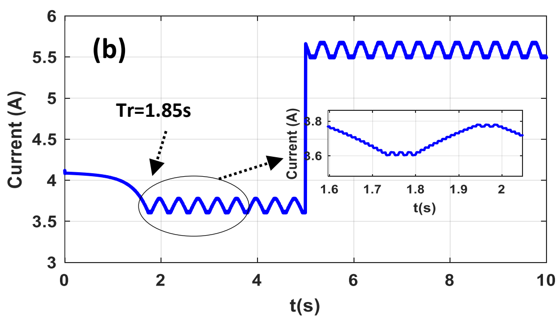

Fig.15b The proposed cascade PI controller response **(b)** PV panel current.

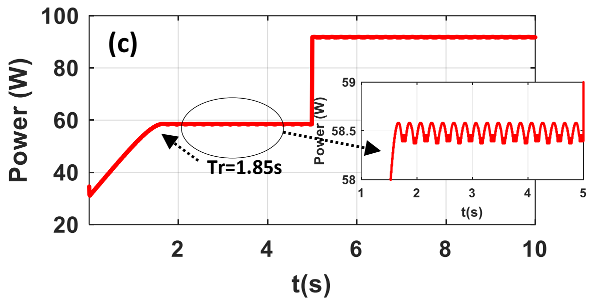

Fig.15c The proposed cascade PI controller response**(c)** PV power extraction.

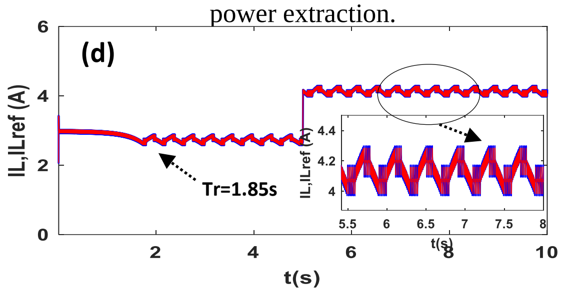

Fig.15d The proposed cascade PI controller response **(d)** inductor current.

The PV output power curve is illustrated in Fig. 5c. We can notice that the PI controller achieves MPP within 1.85 s. However, it can be seen that the controller displays a large ripple waveform along with an overshoot of 0.2 W.

For the inner PI controller exposed in Fig. 5d, the inductor current follows the desired set point ILref in a stabilization time of 1.85 s with high ripples and an oscillation of 0.2 A.

The zoomed views are given in current, power and voltage curves to observe the behavior compared with that of the SMC controller.

- *Response using the sliding mode controller (SMC)*

The MPPT based P & O outputs are a voltage reference that must be tracked by the SMC control, as shown in Fig. 16. The proposed controller is used to track the panel voltage with its reference generated by P & O.

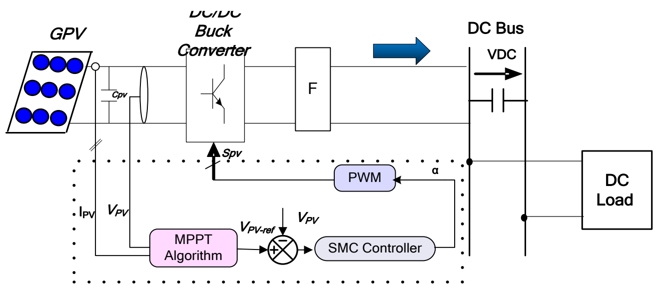

Fig.16. Sliding mode control scheme integrating the MPPT algorithm.

Fig. 17(a–c) exposes the SMC control performance integrating the P & O algorithm under variable radiance. It is observed in Fig. 17(a) that the PV voltage V_{pv} begins to follow its voltage reference $V_{pv\text{-}ref}$ once it has reached steady state after transient behavior and successfully followed the reference voltage in 0.05s.

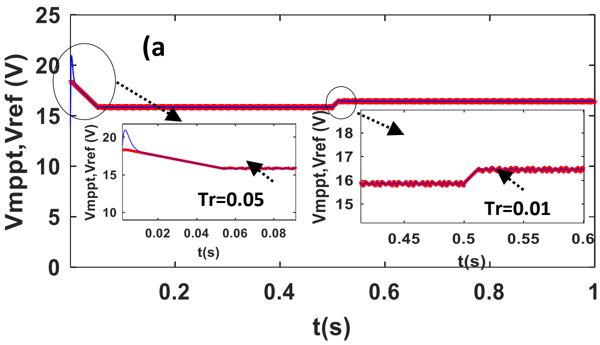

Fig. 17a PV panel voltage profile.

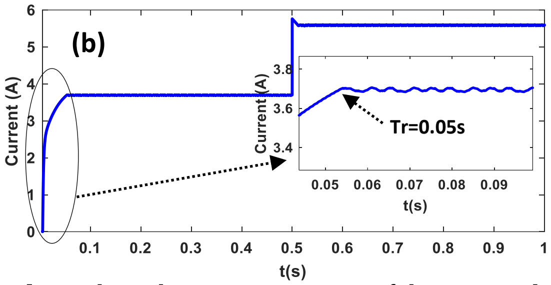

Fig. 17b Tracking the current response of the proposed SMC controller.

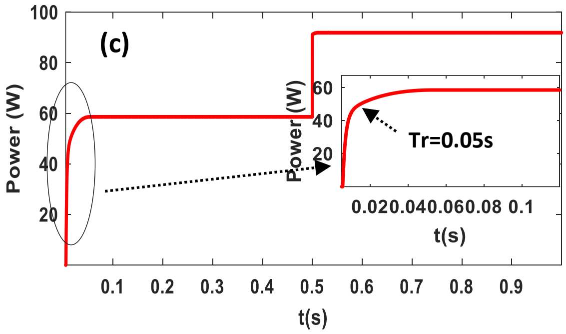

Fig. 17c Profile of MPPT Power Extraction.

Similarly, the output current and power curves of the PV array are exposed in Figs. 17(b-c). We note that PV responses P_{pv} and I_{pv} are fest (t=0.05s). The system's efficiency is significantly improved when the proposed controller is employed.

It is highlighted from the voltage, current, and power PV response curves in Fig. 17(a–c) that the proposed regulator clearly surpasses the PI regulator with few oscillations. During the sudden change in radiance at 0.05 s, the controller performed well, showing its robustness. Furthermore, the ripples are also negligible.

- *Comparative analysis*

Results obtained using an improved SMC controller are free of overshoot and ripples. Compared with the PI regulator, both of them are high and visible.

Table 7 shows that response time and the overshoot characteristics of the SAPS have been explained.

It can be deduced from Table 7 that the SMC performance characteristics in comparison with the PI regulator have been successfully enhanced.

By comparing these results to similar studies in the literature, we discovered:

For example, in [18], it was revealed that the characteristic performance parameters of the SMC controller in comparison with the conventional controller improved successfully, as well as in our study.

As a result, the SMC of this project has produced significantly better results.

In fact, in [18], the Over/Under shoot percentage is 0.6 and the response time (s) is 0.6.

Table 7. Cascade PI and SMC controller characteristics parameters

Regulator	Over/Under shoot (%)	Response Time (s)
PI	5	1.85s
SMC	0.05	0.05s

4. Conclusion

In short, this research work presents the technical, economic and environmental aspects of Stand-Alone Photovoltaic Systems (SAPS) for off-grid electrification in the area of Tunisia. Optimal design and control for this system are also exposed.

Further, this research work suggests that a stand-alone PV system with batteries is a more feasible and optimal solution to ensure reliable, affordable, and eco-friendly electric power to remote areas, particularly the off-grid Tunisian sites.

On the other hand, the economic results of this project are not economically profitable. Several recommendations are suggested for the deployment of a stand-alone photovoltaic system electrification program in Tunisia.

Moreover, the effective application of solar panels requires their characteristics identification under variable climatic conditions. An original experimental set up is carried out in the LPV Lab to identify PV characteristics. Experimental and simulation results performed under MATLAB –SIMULINK software are in good agreement. That shows the effectiveness of the proposed experimental setup.

Further, the control based on sliding mode control for PV systems is synthesized. Simulation results in MATLAB – SIMULINK show a fast dynamic behavior of SAPS with minimal errors, accuracy, and usefulness of the considered control strategy compared with classical PI control.

Therefore, as a short-term prospect, it will be necessary to
- Obtain a robust solar system, an inverter, which is used to supply AC loads (alternating current), must supplement the photovoltaic panels.
- Conduct a more in-depth study on the costs associated with the PV installation analyzed. Try to assess existing solar subsidies and find the optimal subsidy schedule that maximizes net benefits starting in 2023.

Moreover, researchers can consider developing a hybrid renewable energy system, like wind and solar, in this area to make it independent of the national grid.

Future researchers can take a techno-economic and environmental feasibility analysis of SAPS power generation to other regions of the Tunisian country.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships, which might appear to influence the work reported in this paper.

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