

# Determining the Optimum Tilt Angle of Solar Panels and the Energy Produced in the Different Provinces of Burundi

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**How to cite this paper:** Olivier, I., Denis, B., Singh, P., Bosco, N.J. and Noel, N. (2025) Determining the Optimum Tilt Angle of Solar Panels and the Energy Produced in the Different Provinces of Burundi. *Journal of Power and Energy Engineering*, 13, 11-35. <https://doi.org/10.4236/jpee.2025.135002>

**Received:** April 7, 2025

**Accepted:** May 20, 2025

**Published:** May 23, 2025

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## Abstract

Burundi's national electricity production is 130.969 MW, of which 8.979 MW comes from solar energy. This project was carried out to develop models that can be used to calculate the optimum yearly tilt of inclination of fixed solar panels and the maximum energy produced in the provinces of Burundi. When it comes to solar installation projects, people in the sub-region do not have a model for calculating the optimal tilt angle of inclination of solar panels from one site to another, and often position solar panels on the roofs of houses in the case of residential solar systems at an inappropriate angle. In this project, we used meteorological data and geographical coordinates available for the year 2020, which were obtained using the PVGIS5.2 software. Using the R method in SPSS software based on a linear regression model, we have developed a model for calculating the annual available energy on a fixed solar panel at various tilt angles. The results obtained show that the optimal yearly tilt angle of inclination of the solar panel in Burundi varies from 13° to 15.8° depending on the geographical location within the country. We also evaluated the energy production from a 30° tilt angle (which corresponds to the average tilt angle for the roof of a house in Burundi) and compared it to that for an optimally tilted solar panel. In our research, we have also developed a method based on a P&O MPPT controller combined with fuzzy logic (FLC) that corrects the limitations of conventional algorithms according to the climate changes that are occurring worldwide. Taking into account climate change, which affects fixed solar panels inclined at an optimal angle we have designed and simulated an MPPT controller based on the P&O MPTT algorithm combined with fuzzy logic controller. Simulation results show the efficiency of the algorithm developed com-

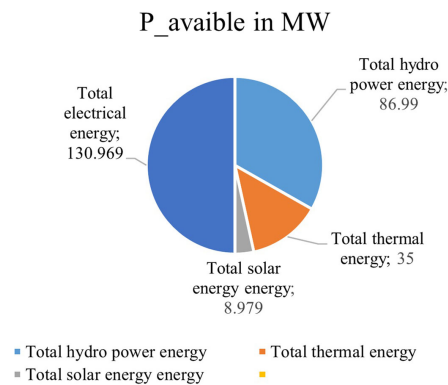
pared with a PWM controller and provides good reference power tracking. Experiments were conducted to measure the energy output and validated the simulated results. The optimal in Burundi offering a 20% energy gain compared to a standard 30° tilt angle for rooftops.

## Keywords

Tilt Angle, Solar Panel, Pvsyst, Solar Radiation, MPPT

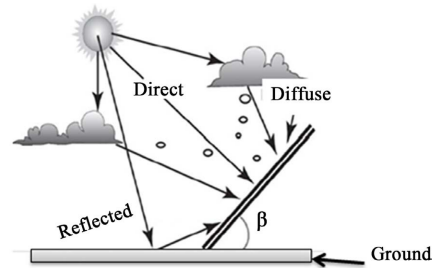
## 1. Introduction

Man has long understood the benefits of harnessing solar energy sources to provide the electricity the world needs for all income-generating activities. In 1839, the French physicist Edmond Becquerel was the first to observe the photovoltaic effect when he noticed that certain materials produced small amounts of electricity current when exposed to light [1]. This principle of photovoltaic energy is based on the technology of semiconductors oriented towards the sun. Electricity generation in Burundi is presently insufficient to meet the country's needs. According to data from the Ministry of Energy and Mines' report for 2023 in Burundi, the country generates 95.96 MW of electrical energy from three main sources: hydroelectric power, thermal energy and solar energy. **Figure 1** illustrates the distribution of electrical energy generated in Burundi [2].



**Figure 1.** Distribution of electrical energy generated in Burundi.

For solar panels to produce maximum energy, the sun's rays must be perpendicular to the solar panel and oriented according to the hemisphere [3] [4]. Authors [5] and [6] shows the influence of irradiation on the energy produced by solar panels in Greece. Author [7] gives four types of solar radiation: the direct solar radiation comes directly from the sun and undergoes little change of direction; the diffuse solar radiation is the radiation that arrives at ground level after having suffered collisions with atmospheric constituents; the reflected solar radiation reflects of the earth's surface and the global solar radiation. Based on **Figure 2**, the global solar radiation is the sum of the three radiations named above.



**Figure 2.** Global solar radiation [7].

Various authors have already explored how to maximize the solar energy output of solar PV systems based on optimizing the tilt angle orientation of the panels. Authors [8] in USA, [9] in China and [10] in Saudi Arabia, show that the tilt angle is close to the latitude of sites in China, USA and Saudi Arabia. Author [11] reports that the optimal annual tilt angle of a photovoltaic cell located in the city of Basra (latitude  $30^{\circ}30''$ ) is equal to  $28^{\circ}$ . Author [12] found that the optimal annual tilt angle for most Palestinian cities is around  $29^{\circ}$ , giving an energy gain of around 10% compared with a solar panel fixed on a horizontal surface. For author [13], a mathematical correlation to estimate the optimum tilt angle for any Indian city as function of its latitude has been proposed. Author [14] notes that for Baghdad (latitude  $33^{\circ}20'$ ), Diyala ( $33^{\circ}14'$ ), and Tikrit ( $34^{\circ}35'$ ) the optimal angle tilt for all sites in Iraqi is the same for  $31^{\circ}$ . Author [15] finds that the optimal angle of inclination at Sukkur located in northern Pakistan is  $29.5^{\circ}$ .

Author [16] in his study finds the yearly optimal tilt angle of some locations in Nigeria were  $20.50^{\circ}$ ,  $20.50^{\circ}$ ,  $21.50^{\circ}$ ,  $20.20^{\circ}$ ,  $21.30^{\circ}$  and  $22.40^{\circ}$ . Author [17] tells that the MOSTAGANEM site in Algeria has a latitude of  $36^{\circ}$ , so the angle of inclination is  $40^{\circ}$ , and if the latitude is less than  $10^{\circ}$ , the angle of inclination is  $10^{\circ}$ . Taking into account climate change, which affects fixed solar panels inclined at an optimal angle, it is necessary to associate an MPPT controller to the fixed solar panel. Several researches have been conducted on the Maximum power point trackers (MPPT) technology for a PV system.

Author [18] have carried out a comparative study of several Maximum Power Point Tracker (MPPT) control techniques, including: the most widely used classical P&O (Perturbation and Observation) method; intelligent meta-heuristic methods; PSO (Particle Swarm Optimization) and GWO (Grey Wolf Optimization). Their simulation results show that the PSO technique gives the best performance compared with the other methods. Author [19] in his study develop hybrid model based on fuzzy logic controller. These technique hybrid techniques are highly efficient compared to conventional methods but are more complex in design. At Burundi, the orientation of the solar panels does not take into account the optimal angle of inclination of the fixed panel, generally when the solar panel is installed on the roof of a house. The angle of inclination of house roofs varies from  $45^{\circ}$  to  $12^{\circ}$  [20]. It means that energy that could be available is lost. We note that this indicator varies from one region to another, from one month to another. It verifies two hypotheses:

- hypothesis 1: solar panel tilt angle is function of latitude;
- hypothesis 2: effect of optimum tilt angle of the solar panel with a controller MPPT on the energy available.

Based on geographical differences across Burundi, there may be differences in the optimal tilt angle of solar panels installed in different locations.

In this article, the aim is to develop models for calculating the optimal yearly tilt angle of fixed solar panels in different areas of Burundi and to determine the optimum tilt angles that yield the largest energy output at the different locations in Burundi. The aim is also the optimization of photovoltaic yield using MPPT technology taking into account climate change. We will evaluate also the solar radiation in Burundi's communes. Finally, we will identify the site that can give us a good Photovoltaic yield compared with others.

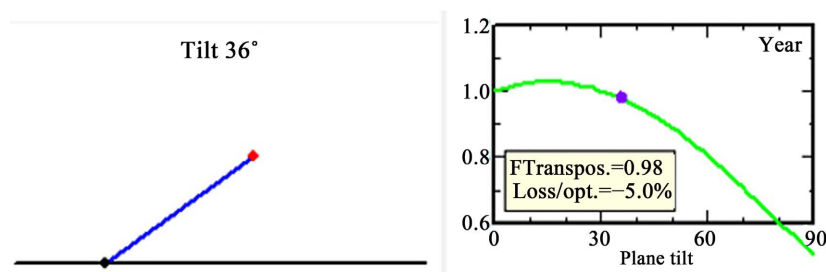
## 2. Method and Materials

### 2.1. Optimization of Photovoltaic Yield by Optimum Panel Tilt Angle

The method is based on the use of monthly meteorological data available up to the year 2020, together with geographical coordinate information obtained using PVGIS5.2 software by entering the name of each site studied in Burundi. The choice of study site depends on which commune in the province has the minimum or maximum latitude. In first, the optimum yearly tilt angle of a fixed solar panel is determined using pvsyst 7.4 software, based on optimization with respect to the yearly irradiation yield and yearly meteorological yield as follows:

- the yearly Transposition Factor (FT), which is the ratio of incident irradiance on the plane to Global Horizontal Irradiation (GlobHor), *i.e.* what you gain by tilting the collector plane. A good transposition factor has a ratio equivalent to 1 or more than 1;
- losses with respect to optimum (Lopt) that we have deemed negligible;
- Global on collector plane (GlobHor\_opt) expressed in %.

The performance ratio (PR) or performance index (PI) is expressed as a percentage and designates the ratio between the actual yield and the theoretical yield of the photovoltaic system. It is generally between 70% and 80% [21]. **Figure 3** illustrates the configuration technique for finding the solar panel's angle of inclination using pvsyst software.



**Figure 3.** Solar panel tilt using pvsyst software.

The R method in SPSS software based on a linear regression model, is used to develop a model for calculating the optimum yearly tilt angle of inclination of the solar panel for calculating the energy available for a solar panel at any site of Burundi. Analysis of the results to test our hypotheses is carried out using the analysis of variance test by simple or multiple linear regressions, which consist in using SPSS software to analyze quantitative variables by determining two coefficients  $R$  and  $R^2$  belonging to  $[-1, 1]$  and a P-value of less than 0.05 [22]. Thus, the European Union's PVGIS (Photovoltaic Geographic Information System Data Base) software, which includes European and African countries on solar radiation data prepared by the Joint Research Center (ECJRC), enables us to obtain meteorological data and geographic coordinate information [23]. We will use also data from the Ministry of Energy and Mines' report for 2023 in Burundi. Pvsyst is a design, sizing and simulation software package suitable for stand-alone and grid-connected photovoltaic and hybrid PV/Diesel systems, as well as DC-grid systems [24]. We will use also MATLAB software [25].

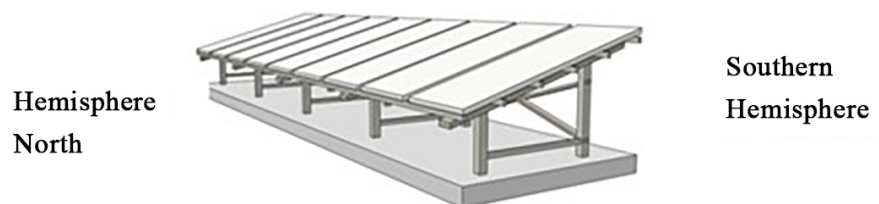
The photovoltaic system under study is simulated using the following components:

- two Sun POWER-SPR-305E-WTH-D silicon-monocrystalline solar panels with the following characteristics: nominal power 305 W, voltage  $V_{oc} = 64.2$  V, voltage  $V_{mpp} = 57.4$  V, current  $I_{sc} = 5.96$  A, current  $I_{mpp} = 5.58$  A, surface area  $1.631$  m<sup>2</sup> weight 18.6 kg, temperature 20°C with a temperature coefficient  $V_{oc}$  of  $-0.27\%/^{\circ}\text{C}$  and a temperature coefficient  $I_{sc}$  of  $0.066\%/^{\circ}\text{C}$ .
- a Universal charge controller with DC-DC MPPT 1000 W 48 V/14A.
- lithiumionsim 48 V 2.4 kw battery manufactured by Turbo energy, 54 V cut-off voltage, 40.5 V discharge voltage, 52 Ah rated capacity.

In the experimental step, we will use a solar panel with the following characteristics:

- Solar panel type sunder S10-18p with maximum power of 10 Wp, voltage  $V_{oc} = 21.24$  V, voltage  $V_{mpp} = 18$  V, short-circuit current  $I_{sc} = 0.62$  A, current  $I_{mpp} = 0.56$  A, temperature = 25°C.

**Figure 4** shows the orientation of the solar panel in the northern hemisphere using Archicad software in all sites of Burundi.



**Figure 4.** Direction of solar panel orientation in all sites of Burundi.

This orientation of the solar panel in the northern hemisphere is due to the fact that Burundi is located in the Southern Hemisphere between meridians  $29^{\circ}00'$  -  $30^{\circ}25'$  East and parallels  $2^{\circ}20'$  -  $4^{\circ}25'$  South, elevation 1614 m with a surface area

of 27,834 km<sup>2</sup> [26].

**Table 1** shows daily meteorological data and geographical coordinates for each site studied. Monthly data obtained using PVGIS v5.2 software, which were converted to daily data using PVSYST software.

**Table 1.** Meteorological data and geographical coordinates for each site studied.

Province	Site	Latitude	Longitude	Altitude	GlobHor	GlobHoropt	Temperature
		(°S)	(°E)	(m)	kWh/m <sup>2</sup>	kWh/m <sup>2</sup>	(°C)
<b>Bujumbura</b>	Kinama	-3.325	29.399	1797	4.91	4.9	22.1
<b>Mairie</b>	Mutanga Sud	-3.38	29.391	900	4.75	4.8	22.6
<b>Bujumbura</b>	Mubimbi	-3.295	29.496	1764	4.61	4.79	19.4
	Kabezi	-3.535	29.345	805	4.66	5.65	19.6
<b>Bubanza</b>	Mpanda	-5.181	31.516	1293	5.57	4.66	21.7
	Musigati	-3.067	29.46	1399	4.78	4.68	17.5
<b>Bururi</b>	Mugamba	-3.665	29.587	2114	4.62	4.64	16.9
	Vyanda	-4.104	29.606	1841	5.02	5.04	18.9
<b>Cibitoke</b>	Mugina	-2.794	29.956	1545	5.07	5.06	21.1
	Buganda	-2.975	29.202	869	4.94	4.95	20.6
<b>Cankuzo</b>	Kigamba	-3.037	30.522	1648	5.36	5.36	20.6
	Cendajuru	-3.313	30.601	1293	5.41	5.41	21.3
<b>Gitega</b>	Nyarusange	-3.568	29.677	1775	4.91	5.19	19.3
	Buraza	-3.478	29.904	1736	4.79	4.97	19.3
<b>Karusi</b>	gitaramuka	-2.981	30.173	1704	5.19	5.17	20
	Shombo	-3.278	30.05	1739	4.96	5.38	20.4
<b>Kayanza</b>	Muhanga	-2.971	28.726	1703	4.71	5.16	20.1
	Butaganzwa	-3.084	29.73	1756	4.84	5.19	20.4
<b>Kirundo</b>	Bugabira	-2.433	30.03	1469	5.38	5.39	21.7
	Vumbi	-2.695	30.08	1679	5.15	5.04	21.1
<b>Makamba</b>	Kayogoro	-4.118	29.95	1397	5.17	4.68	22.2
	Nyanza-Lac	-4.338	29.61	806	5.36	5.31	22.1
<b>Muramvya</b>	Mbuye	-2.154	29.84	1550	5.04	5.26	20.2
	Kiganda	-3.345	29.69	1930	4.39	4.87	19.2
<b>Muyinga</b>	Giteranyi	-2.476	30.47	1634	5.31	4.64	21.3
	Mwakiro	-3.090	30.31	1531	5.26	5.11	21.2
<b>Mwaro</b>	Ndava	-3.378	29.78	1987	4.86	5.19	20.1
	Bisoro	-3.636	29.71	1849	4.34	4.65	20.1
<b>Ngozi</b>	Marangara	-2.731	29.96	1400	5.11	4.77	20.9
	Tangara	-2.914	30.06	1719	5.19	5.27	20.2
<b>Rumonge</b>	Muhuta	-3.570	29.44	2084	4.63	5.54	16.1
	Burambi	-3.814	29.54	1791	4.75	5.28	16.2
<b>Rutana</b>	musongati	-3.727	30.09	1738	5.24	5.34	20.1
	Bukemba	-4.007	30.62	1272	5.51	4.7	22.1
<b>Ruyigi</b>	Butezi	-2.349	30.55	1430	5.28	4.85	21.3
	Kinyinya	-3.657	30.34	1291	5.33	4.9	22.8

## 2.2. Optimization of Photovoltaic Yield Using MPPT Technology

We continue to show our contribution to the optimization of photovoltaic effi-

ciency by introducing MPPT technology. We will show the importance of an MPPT controller compared to a non-MPPT controller. It should be noted that most of the controllers used in Burundi are PWM controllers. An MPPT control algorithm is needed to achieve higher efficiency and continuously extract the maximum available power from the PV module under static, variable and partially shaded weather conditions.

The DC-DC converter using the MPPT algorithm plays a crucial role in the PV system to ensure maximum power transfer between the source and the load, while improving system efficiency. Author [18] [27] discusses the details of DC-DC converters. To simulate the algorithm, we are going to develop, we need a boost chopper described by equations:

$$i_1 = i - c_1 \frac{dV}{dt} \quad (1) [27]$$

$$i_b = (1-D)i_1 - c_2 \frac{dV_b}{dt} \quad (2) [27]$$

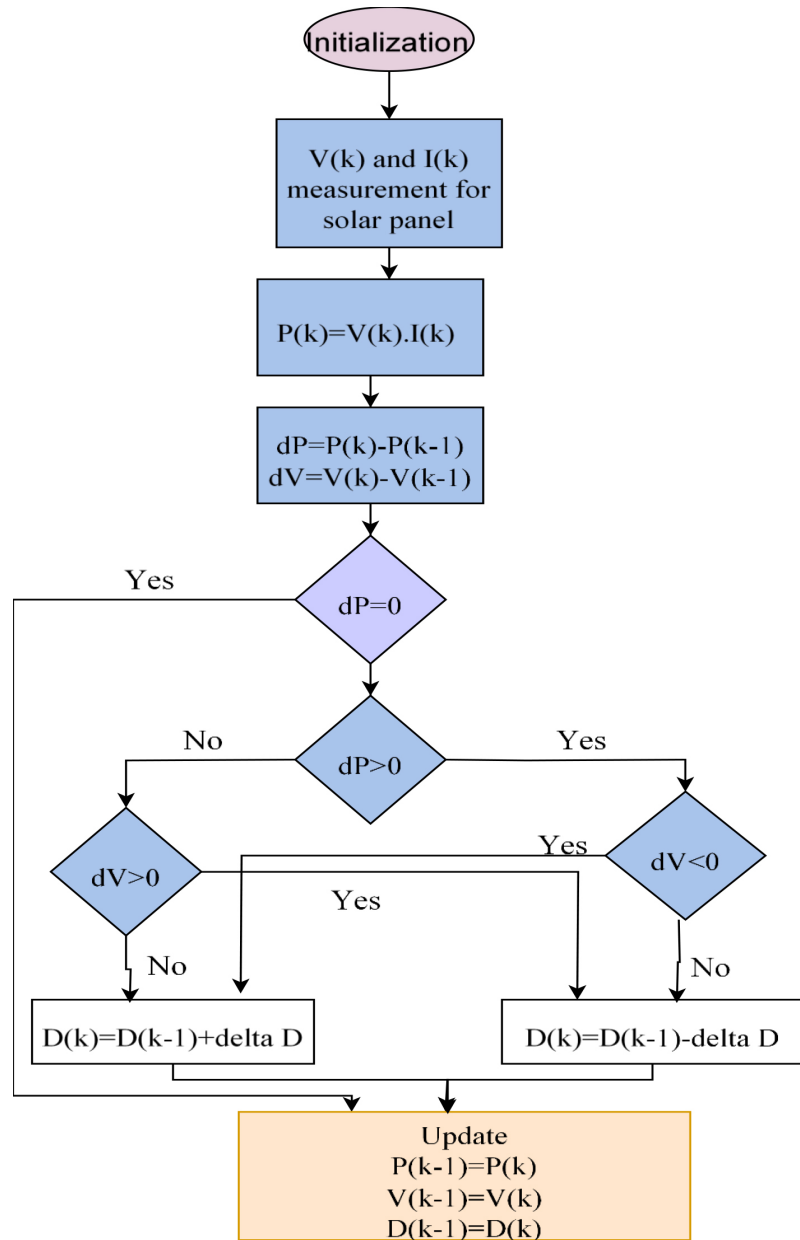
$$V = (1-D)V_b + L \frac{di_1}{dt} \quad (3) [27]$$

where  $D$  indicates the duty cycle of the boost converter, which is the time the switch is closed over period of time. The literature on MPPT techniques proposes several MPPT algorithms that can be divided into two main categories, conventional and non-conventional algorithms [18]. Among the conventional algorithms are the P&O MPPT algorithm and the incremental conductance MPPT algorithm.

### 2.2.1. Conventional Algorithms

The Incremental Conductance MPPT (Inc) is calculated using the derivative of the PV system's power, respecting its voltage, which must be equal to zero at the MPPT; however, it would be positive to the left of the MPPT and negative to the right of MPPT. The P&O method is an iterative technique for MPPT; it measures the photovoltaic characteristics and then perturbs the respective operating point of the PV system to respond to the direction of change [18]. Thus, for the MPPT technique based on the incremental conductance algorithm, the cost of its application is very high and its efficiency is high; but for the P&O MPPT technique, the cost of its application is medium, while its efficiency is very high. Taking into account the average cost of its application and the fact that Burundi is a developing country, in this project we have chosen the MPPT P&O algorithm. The P&O algorithm, exhibit oscillations around the maximum power point due to its disturbance nature. This can lead to system instability and reduced MPPT efficiency as well as overshoot of the optimal maximum point in the event of rapidly changing atmospheric conditions. To overcome these drawbacks, we will combine the MPPT P&O algorithm technique with the artificial intelligence technique based on fuzzy logic.

**Figure 5** illustrates the block diagram of the MPPT P&O algorithm.



**Figure 5.** Block diagram of MPPT P&O algorithm We describe how the MPPT P&O algorithm works. The sign of the power derivative allows us to run this algorithm.

- If the derivative is positive  $dP/dv > 0$ ; increasing the duty cycle  $D$ , indicates that we are approaching MPPT.
- If the derivative is negative  $dP/dv < 0$  the decrease in the duty cycle  $D$ , indicates that we are exceeding the MPPT.
- If the derivative is zero  $dP/dv = 0$ ; this indicates that it is the MPPT.

### 2.2.2. Unconventional Algorithms or MPPT Methods Based on Artificial Intelligence

In recent years, a number of studies have been carried out into more robust control techniques, such as fuzzy logic, neural networks and neuro-fuzzy systems

[28]. Lofti A. Zadeh created fuzzy logic in 1965 based on his theory of fuzzy subsets [29]. The FL (fuzzy logic) approach is based on decomposing a range of variation of a real variable into linguistic variables and assigning a membership function to each variable. The rules developed from the human operator's expertise are expressed in linguistic form.

The proposed FL controller consists of four basic elements:

- Fuzzification is a process by which clearly delimited values are made fuzzy. To perform fuzzification, the variables and linguistic terms to be used must first be defined.
- The membership function is a way of graphically expressing the level of participation of inputs. It assigns a value to the inputs, which can also serve as functional overlaps between the inputs.
- Fuzzy rules: Fuzzy rules are developed to control the output variables in a system that includes a fuzzy logic controller. and defuzzification.
- The defuzzification process is a means of transforming the fuzzy output of the inference block into a clearly defined output by applying membership functions such as those used in fuzzification.

In this project, the fuzzy logic technique was combined with the MPPT P&O technique to control the different variations in solar irradiation due to climate change in order to improve tracking performance in terms of dynamic response and robustness.

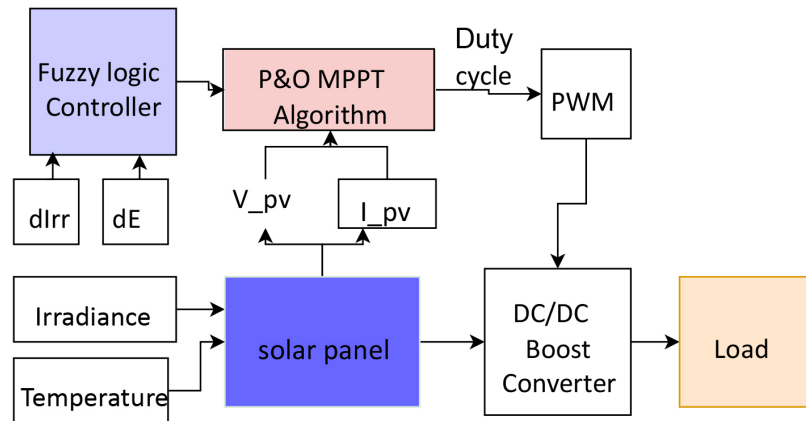
### 2.2.3. MPPT P&O Algorithm Combined with Fuzzy Logic Controller Configuration

Each input/output variable in the fuzzy logic controller is required to define the control surface which can be expressed in fuzzy set notations using linguistic levels. Variables are expressed as (PB: big positive, PM: medium positive, PS: small positive, ZE: zero, NS: small negative, NM: medium negative, NB: big negative). Defuzzification uses the centroid method to calculate the output duty cycle. Our contribution to the MPPT technique consists of combining the MPPT P&O algorithm with fuzzy logic. With fuzzy logic, the method consists of controlling the variation in solar irradiation, in relation to the variation in solar panel voltage in proportion to the variation in solar panel current according to the following equations.

$$dIrr = Irr - \frac{dIrr}{dt} \quad (4)$$

$$dE = \frac{V}{I} - \frac{dV}{dI} \quad (5)$$

where  $Irr$  is solar irradiation,  $V$  is the voltage and  $I$  is the current of the output of solar panel. The values were found after a simulation of the solar system. We recorded the output values of the voltage and current in the solar panel, which enabled us to determine the operating ranges of the variations  $dE$ . **Figure 6** shows the system configuration of the MPPT P&O algorithm combined with fuzzy logic.



**Figure 6.** Block diagram of system configuration of the MPPT P&O algorithm combined with fuzzy logic.

We have parameterized the fuzzy logic controller according the three conditions of climate change:

- ✓ Condition 1: In case a of a large variation in solar irradiation, the value of the increment must be very large so that the system approaches the point of maximum power quickly. In this case, the value of the difference between the voltage/current ratio  $dE$  will be variable and approach zero.
- ✓ Condition 2: In the case of an average variation in solar irradiation, the value of the increment must be neither too large so as not to exceed the point of maximum power, nor too small so that the system does not take many iterations to reach the point of maximum power.
- ✓ Condition 3: In the event of only a small variation in solar irradiance, the value of the increment will be small and will become increasingly smaller until it reaches zero when the value of  $dE$  is zero or negative.

**Table 2** illustrates the rules for membership.

**Table 2.** Rules for membership functions of the fuzzy controller.

		dIrr						
		NB	NM	NS	ZERO	PS	PM	PB
dE	NB	PM	PM	PM	PM	PM	PM	PM
	NM	PM	PM	PM	PM	PM	PM	PM
	NS	PM	PM	PM	PM	PM	PM	PM
	ZERO	PM	PM	PM	PM	PM	PM	PM
	PS	PM	PS	PS	PM	PS	PS	PM
	PM	PB	PM	PS	PM	PS	PM	PM
	PB	PB	PB	PB	PM	PM	PB	PB

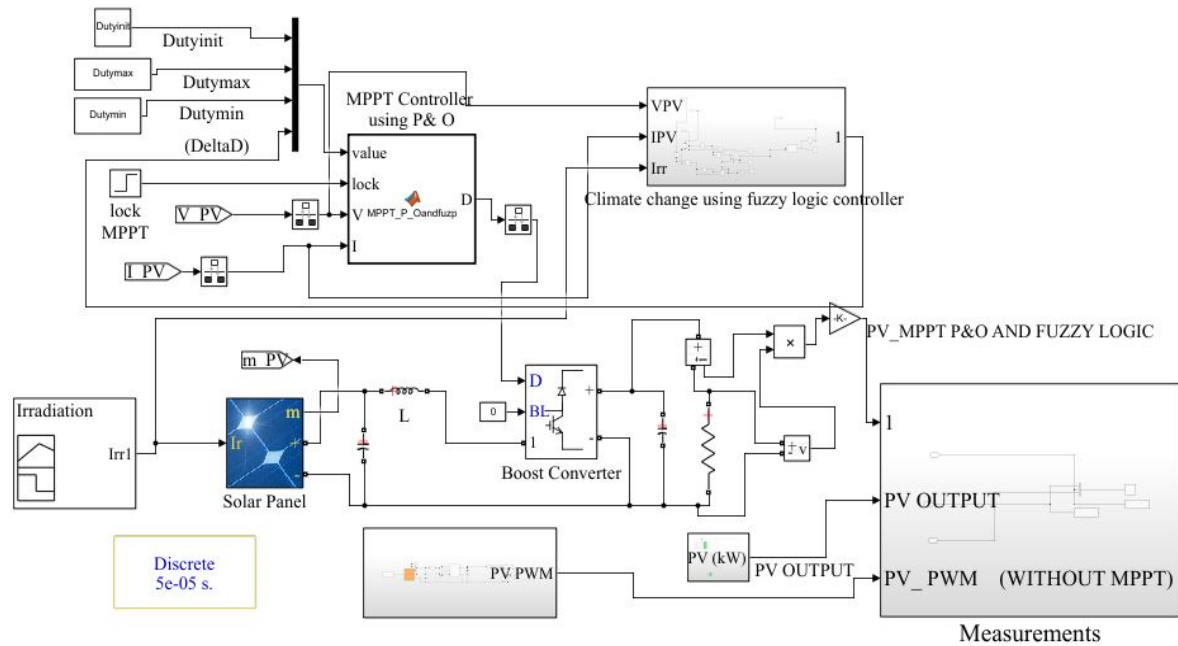
### 3. Results

#### 3.1. Design and Simulation of MPPT Controller

With the rapid climate change in recent years, the power generation efficiency of fixed-angle solar systems with optimal angle will be affected. That is why we in-

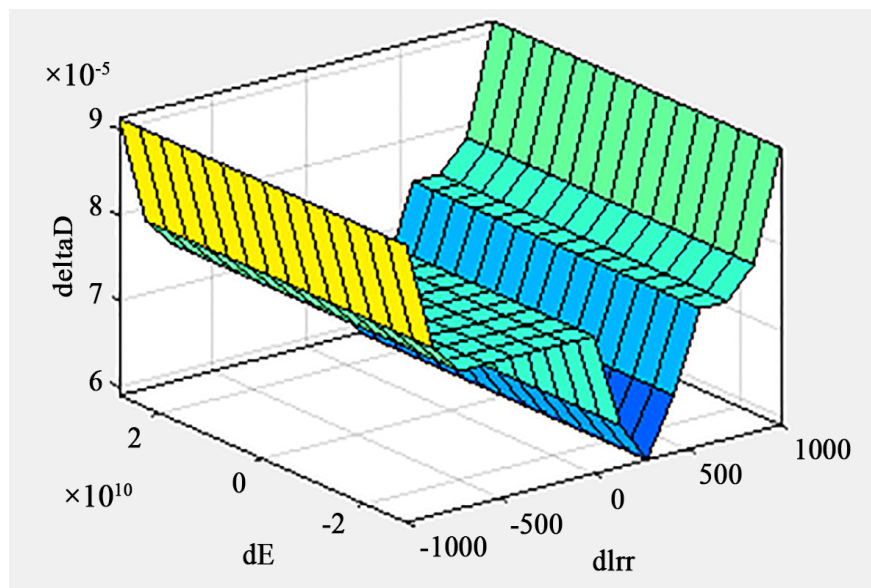
introduce Maximum Power Point Tracking (MPPT) technology to dynamically improve power generation efficiency in this party.

**Figure 7** shows the design of a fixed solar panel system of 610 Wp controlled with the MPPT P&O algorithm combined with fuzzy logic controller in MATLAB.

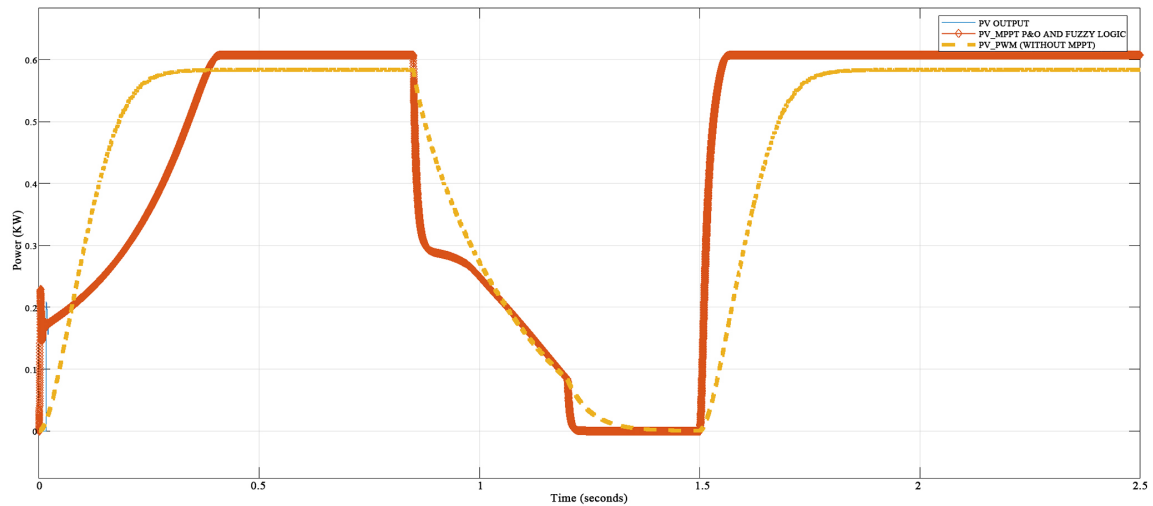


**Figure 7.** Block diagram of the design of fixed solar panel system controlled by the MPPT P&O algorithm combined with fuzzy logic controller.

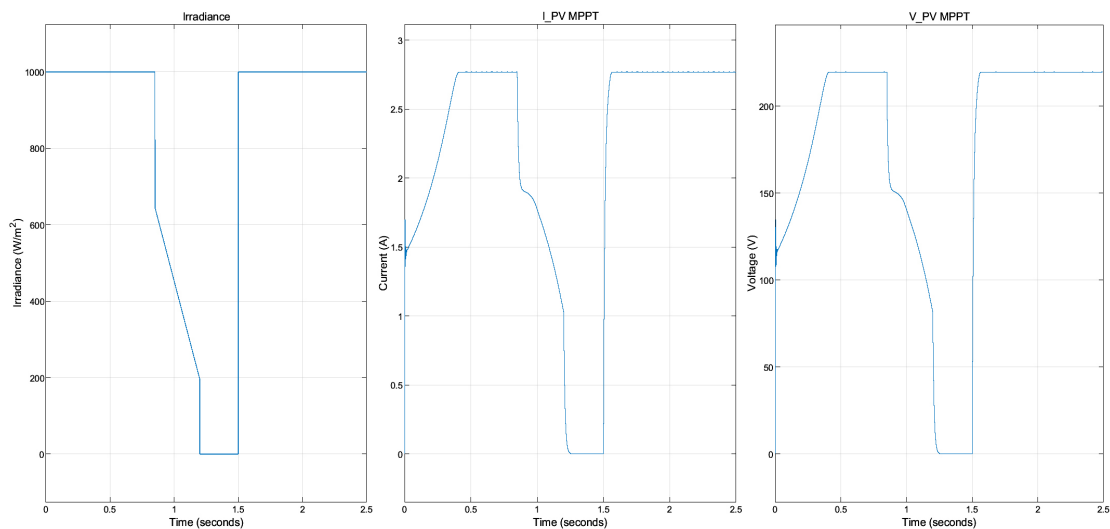
**Figure 8** illustrates the 3D curve of relationships between the inputs and the fuzzy output constructed as a function of the tree conditions.



**Figure 8.** The 3D curve of relationships between the inputs and the fuzzy output.



**Figure 9.** Power output using P&O MPPT algorithm associated with fuzzy logic controller.



**Figure 10.** Curve of variation of the irradiance, current and voltage using MPPT algorithm.

**Figure 9** illustrates the power output of a fixed solar panel for the P&O MPPT algorithm associated with fuzzy logic controller compared with a solar panel without MPPT. **Figure 10** shows Curve of variation of the irradiance, Current and voltage using MPPT algorithm.

Simulation results show variations in current, voltage and power in response to changes in irradiance. This technique, based on the algorithm developed, enables the MPPT to be reached in 0 second and provides good reference power tracking. We can evaluate the effectiveness of the MPPT tracking and the speed with which the system responds to changes in irradiance. A small delay in MPPT tracking is also noticeable.

### 3.2. Optimum Tilt Angle of Solar Panel

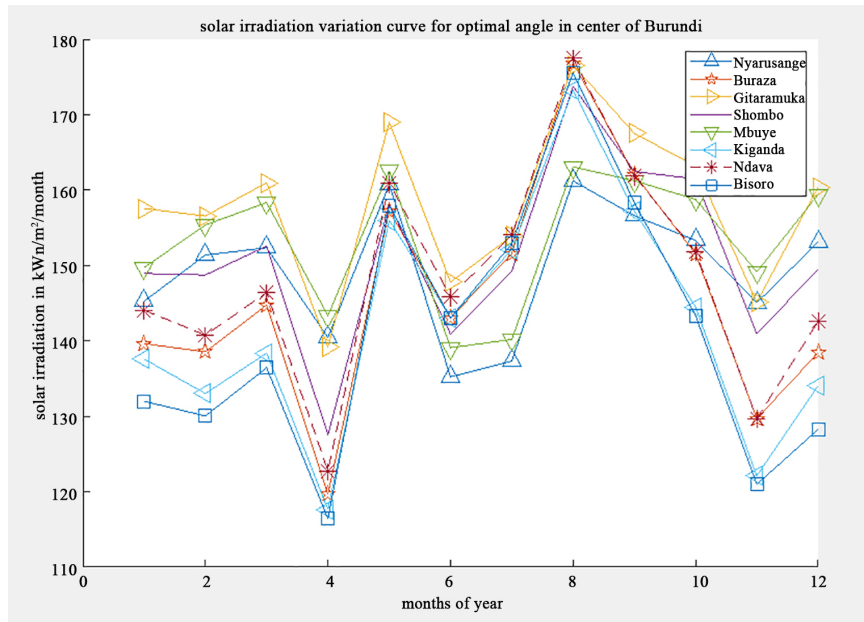
In this section, the yearly optimal tilt angle was calculated using PVSYST 7.4 soft-

ware. Three parameters were evaluated to determine the yearly optimum angle of inclination of the fixed solar panel: the yearly Transposition Factor (FT), the yearly losses with respect to optimum (Lopt) expressed in %, the Global on collector plane (GlobHor\_opt) expressed in kWh/m<sup>2</sup>. **Table 3** shows the optimal solar panel tilt angle for different sites in Burundi. We will evaluate the simulation results of the above-mentioned parameters for an average angle of 30° in relation to the optimal yearly tilt  $\beta_{opt}$  in degrees and their effect on the available energy (E\_Avail).

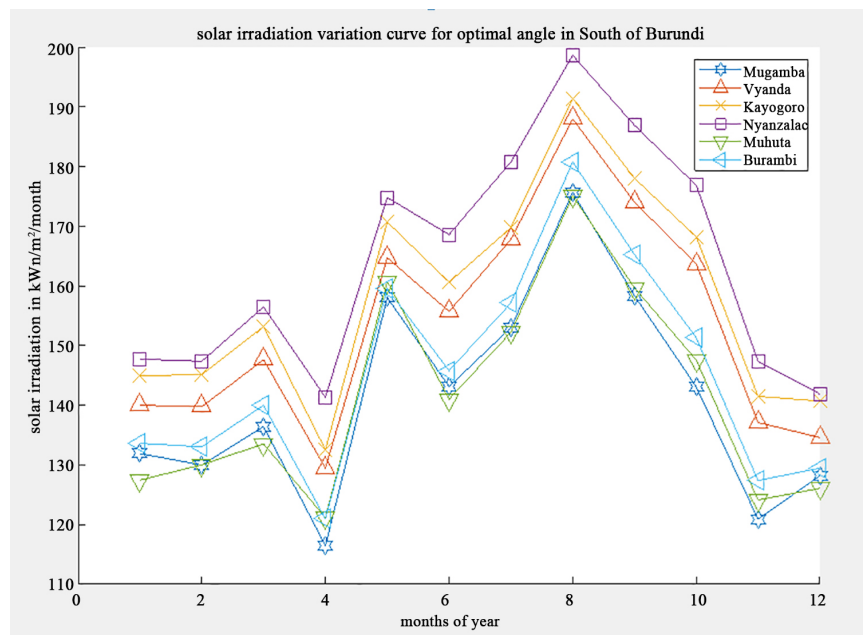
**Table 3.** Optimum yearly tilt angle of solar panel in Burundi's provinces.

Province	Site	Latitude	For 30° angle				For optimal yearly tilt angle					
			FT	Lopt	GlobHor	E_Avail	FT	Lopt	GlobHoro pt	$\beta_{opt}$	E_Avail	RP
		°S	%	%	kWh/m <sup>2</sup>	KWh	%	%	kWh/m <sup>2</sup>	°	KWh	%
<b>Bujumbura</b>	Kinama	-3.325	0.95	5.00	4.5	853	1	0.0	4.76	<b>14</b>	906.5	78.1
<b>Mairie</b>	Mutanga Sud	-3.380	0.96	4.70	4.44	843	1	0.0	4.65	<b>15</b>	884	74
<b>Bujumbura</b>	Mubimbi	-3.295	0.96	4.70	4.45	840	1	0.0	4.67	<b>14</b>	890	73.8
	Kabezi	-3.535	0.96	4.60	4.48	853	1	0.0	4.69	<b>15</b>	903	73.5
<b>Bubanza</b>	Musigati	-3.067	0.95	5.00	4.56	873	1	0.0	4.8	<b>14</b>	930	78
	Mpanda	-5.181	0.98	3.60	5.40	1040	1	0.0	5.67	<b>15.7</b>	1084	75.1
<b>Bururi</b>	Mugamba	-3.665	0.96	4.50	4.44	845	1	0.0	4.64	<b>15</b>	893	74.3
	Vyanda	-4.104	0.97	4.40	4.84	928	1	0.0	5.05	<b>15</b>	968	74.1
<b>Cibitoke</b>	Mugina	-2.794	0.95	5.50	4.79	896	1	0.0	5.07	<b>13</b>	962	74.1
	Buganda	-2.975	0.95	5.00	4.71	892	1	0.0	4.96	<b>14</b>	949	75.4
<b>Gitega</b>	Nyarusange	-3.568	0.95	5.30	4.65	870	1	0.0	4.91	<b>15</b>	933	76.5
	Buraza	-3.748	0.96	4.70	4.59	868	1	0.0	4.8	<b>15</b>	919	78
<b>Karusi</b>	Gitaramuka	-2.981	0.95	5.30	4.92	928	1	0.0	5.19	<b>14</b>	989	78
	Shombo	-3.278	0.95	5.20	4.70	886	1	0.0	4.96	<b>15</b>	944	75.5
<b>Kayanza</b>	Muhanga	-2.971	0.95	5.20	4.47	831	1	0.0	4.71	<b>14</b>	892	73.5
	Butaganzwa	-3.084	0.95	5.00	4.61	870	1	0.0	4.86	<b>14</b>	924	77.2
<b>Kirundo</b>	Bugabira	-2.433	0.95	5.10	5.12	953	1	0.0	5.39	<b>13</b>	1014	75.1
	Vumbi	-2.695	0.96	4.70	4.94	921	1	0.0	5.19	<b>13</b>	978	77.4
<b>Muyinga</b>	Giteranyi	-2.476	0.95	5.40	5.01	933	1	0.0	5.3	<b>13</b>	996	76.4
	Mwakiro	-3.090	0.95	5.40	4.97	929	1	0.0	5.26	<b>14</b>	992	77
<b>Ngozi</b>	Tangara	-2.914	0.95	5.30	4.92	924	1	0.0	5.19	<b>14</b>	986	77.6
	Marangara	-2.731	0.94	5.50	4.82	906	1	0.0	5.1	<b>13</b>	965	79.3
<b>Makamba</b>	Kayogoro	-4.118	0.96	4.60	4.97	924	1	0.0	5.2	<b>15</b>	976	77.2
	Nyanza Lac	-4.338	0.96	4.50	5.17	965	1	0.0	5.4	<b>15</b>	1018	74.8
<b>Muramvya</b>	Mbuye	-2.154	0.94	6.4	4.71	896	1	0.0	5.04	<b>12</b>	958	74.7
	Kiganda	-3.345	0.96	4.80	4.19	796	1	0.0	4.41	<b>14</b>	844	75.5
<b>Mwaro</b>	Ndava	-3.378	0.96	4.90	4.64	877	1	0.0	4.87	<b>14</b>	930	76.9
	Bisoro	-3.636	0.96	4.60	4.44	833	1	0.0	4.64	<b>15</b>	880	74.2
<b>Rumonge</b>	Muhuta	-3.570	0.96	4.40	4.46	839	1	0.0	4.66	<b>15</b>	885	74
	Burambi	-3.814	0.96	4.50	4.58	863	1	0.0	4.78	<b>15</b>	910	77
<b>Rutana</b>	Musongati	-3.727	0.97	4.20	5.09	953	1	0.0	5.30	<b>15</b>	1002	75.2
	Bukemba	-4.007	0.97	4.40	5.33	998	1	0.0	5.56	<b>15</b>	1050	76.6
<b>Ruyigi</b>	Butezi	-2.349	0.95	5.40	4.99	930	1	0.0	5.27	<b>13</b>	995	76.9
	Kinyinya	-3.657	0.95	5.40	5.04	940	1	0.0	5.33	<b>15</b>	1003	76
<b>Cankuzo</b>	Kigamba	-3.037	0.95	5.30	5.07	950	1	0.0	5.35	<b>14</b>	1013	75.5
	Cendajuru	-3.313	0.95	5.20	5.13	964	1	0.0	5.4	<b>14</b>	1026	74.6

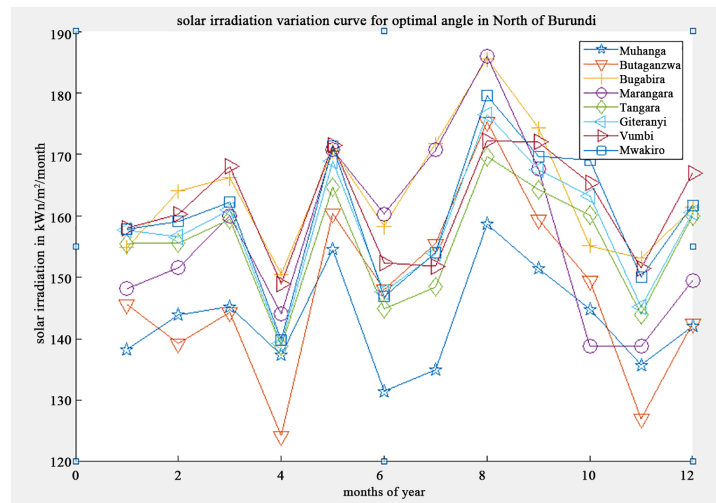
The simulation results show that the optimum yearly tilt angle for fixed solar panels in the provinces of Burundi range from  $12^\circ$  to  $15.7^\circ$ . The results show losses for the  $30^\circ$  tilt angle, while for the optimal yearly tilt the transposition factor is 1 and losses relative to the yearly optimum are zero and remain constant, while the global on collector plane varies as a function of tilt angle in all the sites studied. We note a performance index (PR) for all sites ranging from 73.5% to 79.3%. **Figure 11** shows the variation in overall horizontal irradiation (data obtained using PVGIS) for the optimum angle for the sites studied.



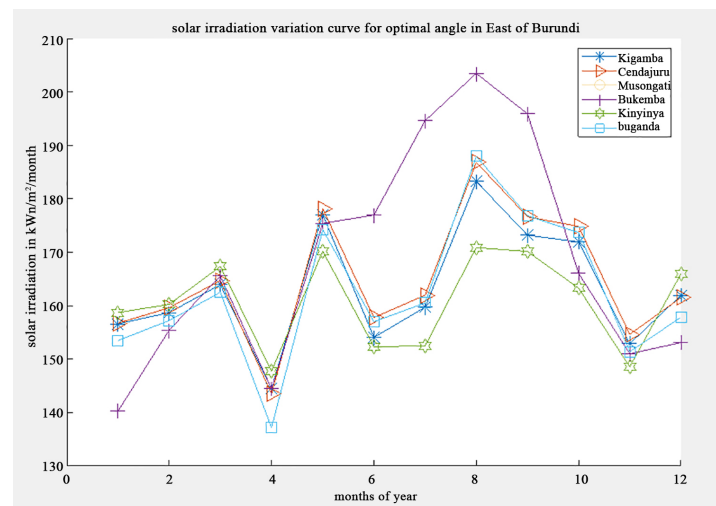
(a)



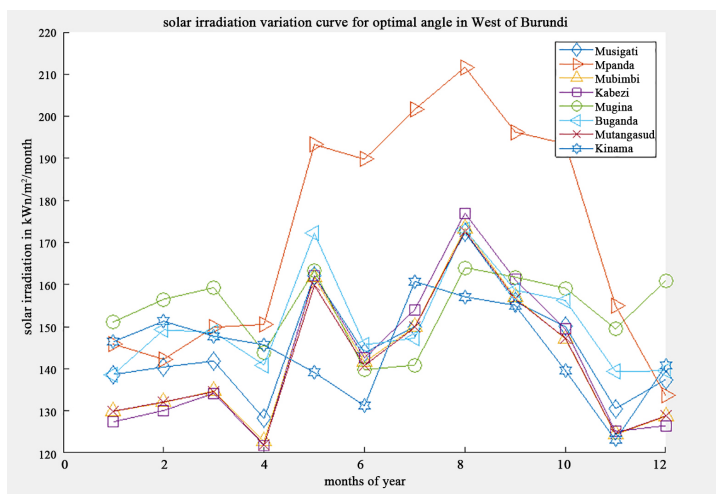
(b)



(c)



(d)



(e)

**Figure 11.** Variation in optimum horizontal global irradiance (a) in Center, (b) in South, (c) in North, (d) in East and (e) in West of Burundi.

Based on the results obtained using MATLAB software, the curves show that all the provinces of Burundi have a high solar energy yield all year round. We notice that only Mpanda, Marangara, Bukemba and Nyanza-Lac have a high solar energy yield from May to September.

### 3.3. Effect of Optimal Solar Panel Tilt Angle on Energy Output

In this section, we have also evaluated the effect of the solar panel's tilt angle on the energy captured for one of the sites studied. **Table 4** shows the results obtained on the effect of solar panel tilt angles on the energy produced at the Marangara site.

**Table 4.** Table of the effect of solar panel tilt angles on the energy produced at the Marangara site.

Site	Latitude (°S)	GlobHor (kWh/m <sup>2</sup> /day)	Angle (°)	E_Avail (kWh/yr)
Marangara	-2.731	5.1	13	965
Marangara	-2.731	5.06	18	953
Marangara	-2.731	4.94	25	926
Marangara	-2.731	4.82	30	900
Marangara	-2.731	4.67	35	868
Marangara	-2.731	4.3	45	791
Marangara	-2.731	4.08	50	750

We see that the energy produced for the optimum tilt angle of the solar panel is significant compared with the other angles.

**Table 5** and **Table 6** illustrate the main balances and results for solar panel tilt at an angle of 30° and an optimum angle of 13° at the Marangara site.

**Table 5.** Main results for a 30° solar panel tilt angle.

	GlobHor	GEff	E_Avail	EUnused	E_Miss	E_User	E_Load	SolFrac
	kWh/m <sup>2</sup>	kWh/m <sup>2</sup>	kWh	kWh	kWh	kWh	kWh	Ratio
<b>Year</b>	1863.4	1668.4	900.33	22.33	46.92	845.14	892.06	0.947

**Table 6.** Main results for 13° solar panel tilt angle.

	GlobHor	GEff	E_Avail	EUnused	E_Miss	E_User	E_Load	SolFrac
	kWh/m <sup>2</sup>	kWh/m <sup>2</sup>	kWh	kWh	KWh	KWh	kWh	Ratio
<b>Year</b>	1863.4	1791.2	964.61	34.47	0	892.06	892.06	1

Where E\_Load is Energy for Load, GEff is Effective Global, SolFrac is Solar Fraction, Eunused is Unused Energy, E\_User is Energy Supplied to the use, E\_Miss is Missing Energy and GlobHor Global Horizontal irradiation.

The results obtained show that the energy required (load) is 892.06 kWh/year. For the optimum yearly tilt angle of inclination of 13°, the energy available is 964.61 kWh/year and we have the energy demanded (load) of 892.06 kWh/year which corresponds to the energy given to users. For the angle of inclination of 30°,

the energy produced is 900.33 kWh/year with the energy given to users of 845.14 kWh, which is less than the load energy (892.06 kWh/year).

### 3.4. Performance Ratio (PR)

Figure 12 shows the monthly and yearly values of the performance ratio obtained for the Marangara site.

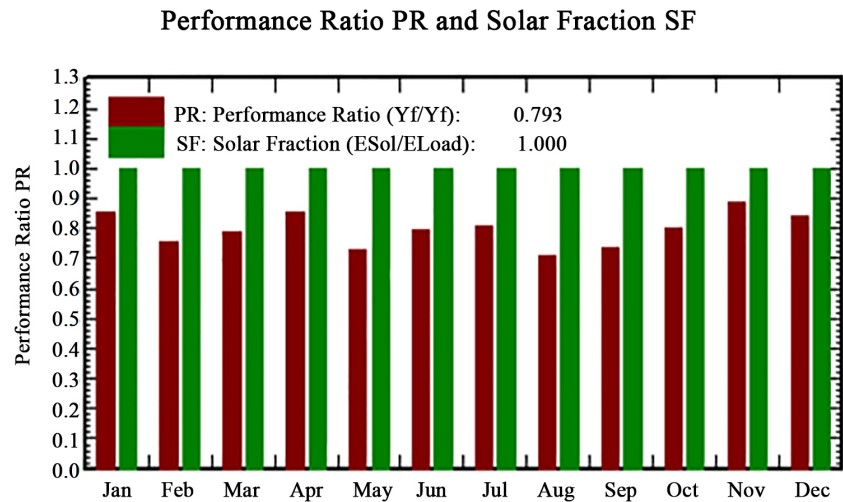


Figure 12. Photovoltaic field performance index.

We obtained a PR ranging from 73.5% to 79.3% in our study (see Table 2), which shows that Burundi has a significant yield on the photovoltaic system. Figure 8 shows a PR of 79.3%, which means that around 21.7% of the energy radiated during the observation period could not be used, due to losses such as 2.98% unused battery energy, 10.35% solar panel collection loss and 7.37% system loss, as detailed by a loss diagram.

### 3.5. Developed Optimum Tilt Angle Model, Developed Available Energy Model of Solar Panels and Analysis of Results

In this section, we will show the novelty of the project. Using the R method in SPSS software based on the linear regression model, we will develop a model for calculating the optimum yearly tilt of inclination of the solar panel and a model for calculating the energy available for a solar panel at any site with a latitude of less than 10. We will analyse whether the input parameters to the models allow us to obtain an output value applicable to each site studied based on the linear regression model.

#### 3.5.1. Analysis of Tilt Angle Results and Developed Optimum Tilt Model

Analyzing the results in Table 3 using SPSS software to verify that the solar panel tilt angle varies with latitude. The input parameters are the latitude of the site and the angle. The angle is a dependent variable. Table 7 shows a summary of the model of the coefficients for determining R.

**Table 7.** Table of a summary of the model of the coefficients for determining R.

Model	R	R-two	R-two adjusted	Standard error of the estimate
1	0.825 <sup>a</sup>	0.681	0.672	0.4918

a. Predictors: (Constant), latitude.

In the regression model, we have a Correlation Coefficient R equal to 0.825 and a Coefficient of determination R<sup>2</sup> equal to 0.681 indicating a relationship between solar panel tilt angle and latitude with an average percentage of 68.1%. **Table 8** illustrates the non-standardized and standardized coefficients and the P-value (sig).

**Table 8.** Table of non-standardized and standardized coefficients.

Model	Coefficients <sup>a</sup>				t	Sig.
	Non-standardized coefficients		Standardized coefficients			
	B	Standard error	Beta			
(Constante)	11.079	0.380			29.150	0.000
1 Latitude (°S)	0.939	0.110	0.825		8.522	0.000

a. Dependent variable: Angle.

From this table, we note a P-value of less than 0.05, showing that there is a statistically significant relationship between solar panel tilt angle and latitude. The mathematical model developed that expresses the solar panel's optimum yearly tilt of inclination for any site studied is:

$$\beta = 0,939.\lambda + 11,079 \quad (6)$$

where  $\beta$  is optimum yearly tilt of inclination (in °); where  $\lambda$  is latitude of the site (in °S). By entering the latitude coordinates of the site under study, we can easily obtain the optimum yearly tilt angle of inclination of the solar panel at each site from this mathematical model.

### 3.5.2. Analysis of the Effect of Angle of Inclination on Captured Energy and Developed Available Energy Model

Analyzing the results in **Table 3** using SPSS software to test the effect of optimum tilt angle of the solar panel on the energy available. The input parameters are the optimum yearly angle, the global horizontal irradiation and the available energy. The available energy is a dependent variable. **Table 9** shows a summary of the model of the coefficients for determining R.

**Table 9.** Table of a summary of the model of the coefficients for determining R.

Model	R	R-two	R-two adjusted	Standard error of the estimate
1	1.000 <sup>a</sup>	1.000	1.000	1.130

a. Predictors: (Constant), Angle, GlobHr.

In the linear regression model, we have a Correlation Coefficient R equal to 1 and a Coefficient of Determination  $R^2$  equal to 1, validating the influence of solar panel tilt angle and overall horizontal irradiance on available energy in the high percentage of 100%. **Table 10** shows the non-standardized and standardized coefficients and the P-value (sig).

**Table 10.** Table of non-standardized and standardized coefficients.

Model	Non-standardized coefficients		Standardized coefficients	T	Sig.
	B	Standard error	Beta		
(Constante)	64.583	32.014		2.017	0.114
<b>1</b> GlobHor (kWh/m <sup>2</sup> )	178.893	5.738	0.851	31.174	0.000
Angle (°)	-0.913	0.164	-0.152	-5.550	0.005

a. Dependent variable: E\_avail.

We note P-values of less than 0.05 for GlobHor and Angle, showing that there is a statistically significant relationship between the variables (tilt angle and global horizontal irradiance) and available energy. From the values of B and Beta, we see a strong positive significant implication for horizontal global irradiation and a weak negative significant implication for solar panel tilt angle on available energy. The mathematical model representing available energy for any site studied is given by the following expression where  $\beta$  is the angle,  $P_C$  power of solar panel in Watt:

$$E_{Avail} = (-0.913 \cdot \beta + 178.893 \cdot GlobHor + 64.583) \cdot \frac{P_C}{610} \quad (7)$$

By entering the values of the yearly tilt angle of inclination of the solar panel and the value of the global horizontal irradiation of the site studied, we can easily obtain the energy available per year for any power of solar panel in each site. **Table 11** shows the verifications of the models developed using the geographical coordinates and meteorological data used in **Table 3**.

**Table 11.** Optimum yearly tilt and energy available using modes developed.

Site	Latitude	GlobHor for 30°	GlobHoropt	Optimum tilt	E_Avail for 30°	E_Avail for optimum tilt
	°S	kWh/m <sup>2</sup>	kWh/m <sup>2</sup>	(°)	(kWh/yr)	(kWh/yr)
<b>Kinama</b>	-3.325	4.5	4.76	14.2	856.63	903.14
<b>Mubimbi</b>	3.295	4.45	4.67	14.17	833	887.07
<b>Gitaramuka</b>	-2.981	4.92	5.19	13.88	917.65	980.36
<b>Nyarusange</b>	-3.568	4.65	4.91	14.42	869.53	929.78
<b>Mpanda</b>	-5.181	5.40	5.67	15.8	1003.2	1064.4
<b>Mbuye</b>	-2.154	4.71	5.04	13	879.7	954.3

In this **Table 11**, we have shown the verification for a few sites, but the models developed verify all the sites studied. We note that the results obtained by the models developed are close the simulation results obtained with pvsyst software.

### 3.6. Experimental Results

In this section, we will evaluate the experimental results of two solar panels of 10Wp with two regulators victron BlueSolar charge controller MPPT 75/10A-12V tilted one at 30° and the other at optimum tilt of 14° at the Nyakabiga site in the locality of Kinama (Table 3) as shown in Figure 13 and Figure 14. Victron MPPT controller is ultra-fast rapid MPPT controller improves solar production compared with PWM charge controller.



Figure 13. Solar panel tilt at 30°.



Figure 14. Solar panel tilt at 14°.

Figure 15 and Figure 16 illustrate the curves of the experimental results obtained for the dates 12/21/2023 and 12/28/2023.

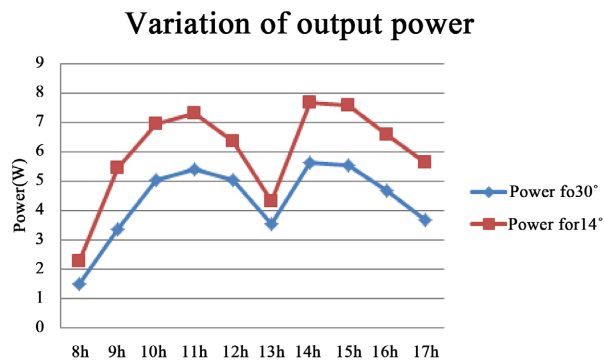
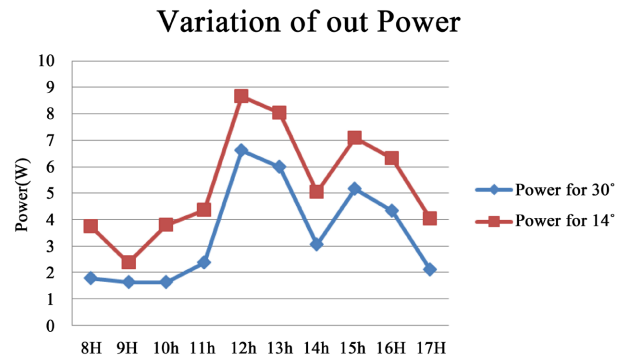


Figure 15. Power variation curve for the 12/21/2023.



**Figure 16.** Power variation curve for the 12/28/2023.

From 9:00 a.m. to 11:00 a.m. and from 2:00 p.m. to 5:00 p.m. for the date 21/12/2023, we notice an increase of around 2W for a solar panel tilted at an angle of 14° compared with the 30° tilt. This increase is also observed for the date 28/12/2023 from 10:00 a.m. to 5:00 p.m., that is a gain of 20%. Under cloudy skies, we observe a significant decrease for all mounts, with a difference of around 0.7 W, the one at 1:00 pm and the second at 2:00 pm. It is mean that there is a lowering of solar irradiation when there is a cloudy sky.

#### 4. Discussions

Some authors have shown that the optimum solar panel tilt angle varies with site latitude, and is close to latitude ([8] [9] [11]-[13]). In our study, the results obtained show also that the optimal yearly tilt angle of the solar panel varies according to the latitude of the site with an average percentage of 68.1%, and that it is not close to the latitude of the site for sites with a latitude of less than 10°. We also note that author [9] in his studies compared the optimum tilt angle with a solar panel fixed on a horizontal surface. We are not sure that this is a good comparison, solar panels are usually not tilted horizontally. Analzsing the simulation results obtained by the models developed, it was found that the model results verify the results obtained by the pvsyst software, which shows the effectiveness of the model. The simulation results showed that for the optimum yearly tilt, the yearly irradiation on the collector plane corresponds to the overall horizontal irradiation of the site obtained using the PVGIS software (Table 1), which demonstrates the effectiveness of the pvsyst software. In relation with [17] for an angle, less than the optimum tilt found, we found that the yearly irradiation on the collector plane is greater than the value of the horozontal global irradiation found by PVGIS5.2 for optimum tilt of the site with a high losses relative to the yearly optimum in Winter. In addition, in this case, the optimal yearly tilt angle of the solar panel does not vary according to the latitude of the site in Burundi. Taking into account climate change, which affects fixed solar panels inclined at an optimal angle all authors have not addressed Maximum Power Point Tracking (MPPT) technology to dynamically improve power generation efficiency. In this project, we have made our contribution by studying a P&O MPPT controller associated with fuzzy logic con-

troller. The P&O MPPT algorithm had a problem with the delay in following the reference. With this algorithm developed, this delay has been eliminated. Although the developed MPPT technique is cost-effective because it improves efficiency and tracking stability of conventional P&O algorithm. It poses many challenges, such as a lower convergence speed, high oscillation around a maximum MPPT power point, the aforementioned drift problem associated with irradiance variation and complex implementation compared to conventional MPPT methods. Authors [30] [31] have conducted studies to reduce these problems. However, the implementation of all these methods is more complex than for conventional MPPT techniques. The simulation results show the effectiveness of the algorithm developed, which provides good reference power tracking.

Analyzing the experimental results found at Nyakabiga in the locality of the Kinama site, where the optimal yearly tilt is  $14^\circ$ , as shown in **Table 10**, to test the proposed model. Adapting it to the results in **Table 11** and equation 7, the daily energy available for an optimum yearly tilt of  $14^\circ$  for a 10 Wp solar panel used in the experiment is 40.5 Wh/day. The daily energy available of a 10 Wp for  $30^\circ$  is 38.47 kWh/day. We found an energy gain of 20.2% for the model simulation results. For the experimental results, we have found an energy gain of 20%. We note that the results from model simulation and experimental results are matched, which shows the effectiveness and validation of the models developed.

## 5. Conclusions

Burundi is a developing country, which currently has a national electrical power generation capacity of 130,969 MW, 6.8% of which comes from solar energy. The government has already opened the door to international companies to invest in renewable energy because only one company was a monopoly in the sale of electrical energy. Most Burundians install solar panels on the roofs of their homes, and do not have a model for calculating the angle of inclination of solar panels. In this project, we began to determine the optimum yearly tilt of inclination of the panel using the pvsyst software. Using the R method under SPSS software based on the linear regression model, we developed a model for calculating the optimum yearly tilt of inclination of the solar panel and a model for calculating the available energy adapted for each site in the country. We found that the optimal yearly tilt of the fixed solar panel in Burundi varies from  $13^\circ$  to  $15.8^\circ$  and varies according to the latitude of the site with an average percentage of 68.1%. We found an energy gain of 20.2% for the model simulation results and an energy gain of 20% for the experimental results, which shows validation of the models developed. We note that the results from model simulation and experimental results are matched to the results obtained by the pvsyst software and experimental results. In relation to the novelty, this project contributes to easily find the optimal tilt angle of the solar panel and the energy available using models developed for each site whose latitude is less than  $10^\circ$ . Another novelty compared to existing work is the introduction of MPPT technology based on P&O MPPT algorithm associated with fuzzy logic

controller to dynamically improve power generation efficiency. The MPPT controller studied have many advantage over the PWM controller used usually in Burundi. We presented the assumptions, constraints and algorithm complexities. The algorithm developed has the advantage of being robust and relatively simple to design, as they do not require knowledge of the exact model. It also requires no training data, which means it can work for different types of PV modules with the same MPPT design. The MPPT algorithm developed in this research can be applied to any site in the world.

We have also show the site in Burundi that have sufficient photovoltaic efficiency. This project contributes also to the national, regional and international community for the social impact of rural electrification in Burundi by having a model for calculating the optimal production of solar-generated electricity. The importance of this project is to raise public awareness of the exploitation of solar energy at an optimum tilt of inclination of the solar panel at these sites, which is in the interests of the environment, the health of the population, the economy of the country, the economy of families, and the interests of entrepreneurship and the social economy. The results of this project will be a good reference for the study of the gain of the solar tracker compared to the fixed solar panel for the future project of integration of solar tracker with battery management in Burundi supported by an Erasmus+ grant and the doctoral school of Burundi.

## Acknowledgements

Erasmus+ and Doctoral School of Burundi supported this project.

## Authors' Contributions

**Bukuru Denis:** Conceptualization, Methodology, Supervision, Project administration, Validation, Writing—review and editing;

**Pritpal (“Pali”) Singh:** Conceptualization, Methodology, Supervision, Project administration, Validation, Writing—review and editing;

**Niyonzima Jean Bosco:** Supervision, Project administration, Writing—review and editing, Validation;

**Ntawuhorakomeye Noel:** Supervision, Project administration, Writing—review and editing, Validation.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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