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Energy Harvesting on Airport Pavements Ambient Dependent: Ponta Delgada Airport Case Study

Diogo Correia and Adelino Ferreira *

Research Center for Territory, Transports and Environment, Department of Civil Engineering, University of Coimbra, 3030-788 Coimbra, Portugal
* Correspondence: adelino@dec.uc.pt

Abstract: Energy transition is an important issue for countries trying to meet their greenhouse gas (GHG) emission targets. To achieve this reduction, the Portuguese government has budgeted a total of EUR 116 M to aid energy transition in the Autonomous Region of the Azores by 2029. This work presents a solution for producing electricity using photovoltaic panels (PV) to settle in the top of the airport pavement. In addition to producing sustainable electricity, the implementation of panels in the civil airport infrastructure allows us to address the reduction of emissions in the ICAO's Carbon Offsetting and the Reduction Scheme for International Aviation (CORSIA) program. Currently, PV panels are unable to support the weight of aircraft so the installation must be in the areas of the pavement where there is no regular aircraft traffic. As a result of the study, a production of about 9 GWh/year was achieved with an LCOE of 143 EUR/MWh, reducing emissions to about 6-ton CO_2/year.

Keywords: airport pavement; energy harvesting; photovoltaic panels; sustainable energy production

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1. Introduction

Correia and Ferreira [1] showed that energy harvesting systems for airport pavements are sustainable and can be performed in two different ways: ambient dependent and traffic dependent [2–6]. The ambient dependent method considered in this paper is a commercial solution produced by Colas, Wattway [7] and the pilot installation from Qilu Transportation Group Co., Smart Road [8], which had involved the insertion of photovoltaic (PV) panels on the top of the pavement. The researchers selected this solution as it is possible to apply on the existing airport pavement [1]. Although the company has only applied its product on road pavements to date, the similarities between road pavement and airport pavement [9] means that PV panels can be used on airport pavements. Due to the force exerted by the tire on the pavement and the potential risk to the aircraft and passengers, the placement of PV panels was limited to areas surrounding the landing path and circulation of the aircraft tires.

Recently different approaches have been developed for the use of airport space with the placement of conventional PV panels [10,11], with solutions that permit the energy autonomy of the facilities by using batteries [12]. This research focuses on the study of PV panels being settled on the top of the pavement, taking advantage of the existing structure to produce electrical energy. Although this research focuses on producing electrical power, batteries can be added to make installations energetically autonomous or local projects can be set up to create storage plants [13].

PV panels are devices composed of PV cells connected in series or parallel. These two types of connections create a physical device, the PV panel, with voltage, electrical, current, and physical component values that meet the needs of the intended application. Various PV panels, independent physical components, can then be connected in series and parallel combinations to meet the requirements of the electrical conversion equipment (grid inverter) or for direct electrical consumption.

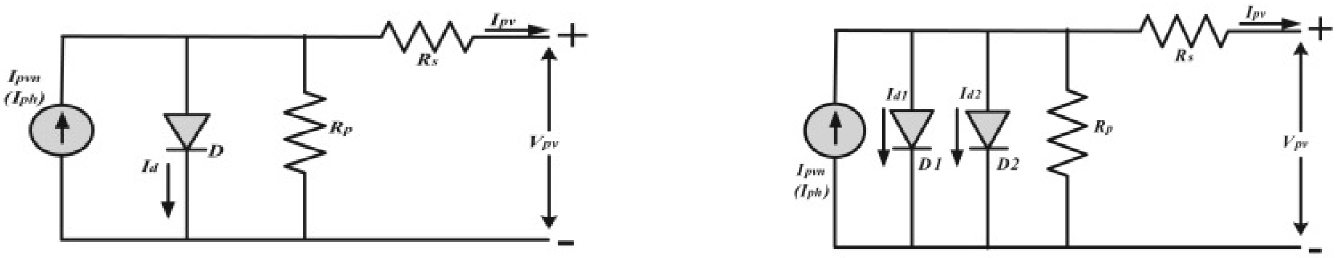
The energy production of each photovoltaic cell, and consequently each photovoltaic panel, depends on the solar irradiation and temperature of the PV cells on characteristic curves provided by the manufacturer, with variations resulting from the production process. PV panels also include reverse current protection elements, which are bypass diodes placed in parallel to the PV panel, inversely to the energy flow that enters conduction when a reverse current occurs, thus protecting the PV cells that make up the PV panel. Despite containing bypass diodes located in the string connection box, the operational range is limited, and there may be a need for external assistance. In this case, the recommendation is to perform this with a fuse when more than two panels are connected in parallel. The use of a bypass diode in the panel and the fuse in series could be replaced by a diode in series, in the direction of energy flow. However, the diode would reduce production, thus reducing the efficiency of the system.

This paper will first present a brief description of the PV panel, which will then count as input data the values given by the company marketing the ambient dependent energy harvesting solution [7]. Next, the possible implementation in the airport pavement selected as a case study is presented with the energy production capacity generated by this type of equipment in the chosen location. We have chosen the airport site because it is on an island with electricity partially produced from fossil fuels.

2. Photovoltaic Panels

Mathematical models are used to understand the behavior of PV panels. As mentioned in the previous chapter, the PV panel comprises PV cells grouped in series or parallel.

Pillai and Rajasekar [14] present a literature review referring to several models that characterize the PV cell but state that the most remarkable PV cell models are the single diode (SD) model (Figure 1a) and double diode (DD) model (Figure 1b).



(**a**) (**b**)

Figure 1. PV cell (**a**) single diode model, and (**b**) double diode model [14].

For Figure 1a the construction of the equation starts with the node analysis by Kirchhoff's current law:

$$I_{pv} = \mathrm{I}_{pvn} - I_d - \frac{V_{pv} + R_s I_{pv}}{R_p} \tag{1}$$

Pillai and Rajasekar [14] apud [15–17] for expressing the diode current as:

$$I_d = I_0 \left[\exp\left(\frac{V_d}{\alpha V_t} \right) \right] - 1 \tag{2}$$

The authors also say that:

$$V_T = \frac{N_S K T}{q} \tag{3}$$

By Ohms laws, the value of V_d is expressed as:

$$V_d = V_{pv} + I_{pv} R_s \tag{4}$$

For a single cell ($N_S = 1$), Equation (5) summarizes Equations (1)–(4):

$$I_{pv} = \mathrm{I_{pvn}} - I_0\left\{\exp\left(\frac{q(V_{pv} + I_{pv}R_s)}{\alpha KT}\right) - 1\right\} - \frac{V_{pv} + R_s I_{pv}}{R_p} \quad (5)$$

Figure 1b follows the same steps as described in Equations (1–4), resulting in Equation (6), expressed as:

$$I_{pv} = \mathrm{I_{pvn}} - I_{01}\left\{\exp\left(\frac{q(V_{pv} + I_{pv}R_s)}{\alpha_1 KT}\right) - 1\right\} - I_{02}\left\{\exp\left(\frac{q(V_{pv} + I_{pv}R_s)}{\alpha_2 KT}\right) - 1\right\} - \frac{V_{pv} + R_s I_{pv}}{R_p} \quad (6)$$

where:
I_{pv} = Output current (A);
I_{pvn} = Photocurrent (A);
V_{pv} = Output voltage (V);
I_d = Diode current (A);
R_p = Parallel resistance (Ω);
R_s = Series resistance (Ω);
I_{0*} = Saturation current of the diode (A);
V_d = PV cell diode voltage (V);
V_T = Thermal voltage (V);
α_* = Diode ideality factor;
K = Boltzman constant;
T = Ambient temperature (°K);
N_s = Number of cells.

Equations (5) and (6) quantify the electrical energy production supplied by PV panels in the single diode or dual diode models, respectively. Despite this way of calculating the electrical output, the internal values I_{pvn}, I_{0*}, R_p, R_s, and α_* are unknown [14,15]. To overcome that, this research will use simulation software capable of predicting the PV production at the implementation site. Nevertheless, it is essential to say that the output of the PV cell is dependent on radiation and temperature (Equation (5) and Equation (6) [18]).

Given its acceptance by the market, the PVSol software from Valentin Software [19] was chosen with a trial and student version and used in this research. The results are provided below.

3. The Ponta Delgada Airport Case Study

Ponta Delgada Airport serves the island of S. Miguel, Azores, the largest island in Portugal. The challenges of electricity production and the consumption of fossil fuels for this purpose were the reasons for selecting this location, with a view to transferring the findings to other similar areas.

The software used to simulate the implementation of the PV panels was PVSol [19]. PVSol is owned by Valentin Software and relies on the input of climate data from MeteoSyn [20] with meteo data provided by Meteonorm. Pushpavalli [21], who carried out his work comparing different software, states that the energy production values obtained by the PVSol software [19] are similar to SolarGIS [22] and PVGIS [23] software, which additionally supports the selected software.

Due to the existing characteristics, the PV panels will have to fit the available space without interfering with the existing airport pavement features. The possible features were surveyed using the aerodrome chart [14]. Finding no significant obstacles, we proceeded to quantify the total area capable of being exploited for the placement of panels using Google Earth software. Using the existing tools on Google Earth the whole site was selected, resulting in Figure 2, obtained at location N 37°44′33.96″, W 25°41′55.69″.

Figure 2. Installation aerial view overlaid with implementation zone.

A useful area of 56,825 m^2 was measured. To understand the number of PV panels that could be implemented, the characteristics of the panels were surveyed, resulting in Table 1.

Table 1. Wattway PV panel technical data [24].

Wattway Technical Data	
Module size	1257 × 690 mm (0.87 m^2)
Production surface per module	0.69 m^2
Number of active cells	28
Nominal power (Pnom)	125 W$_p$
Maximum power point voltage (Vmpp)	15.1 V
Maximum power point current (Impp)	8.27 A
Open circuit voltage (Voc)	18.5 V
Short-circuit current (Isc)	8.7 A
Maximum system voltage	60 V
Power temp. coefficient (Pmpp)	−0.40%/°C
Inverted current max	15 A
Cells	Monocrystalline

PVSol 3D is limited to a 400 m radius, which is not enough to implement the aerodrome strip of 2443 × 150 m^2 [25] or all the possible airport PV installations. Due to this constraint, a 250 m long and 59.7 m wide segment of the airport pavement was selected to understand how many panels could be placed on this segment. The simulation used the components described in Table 1, where it was possible to quantify that the 3750 m^2 segment can implement 3590 panels. Figure 3 shows the settlement of photovoltaic panels on the pavement segment according to [25].

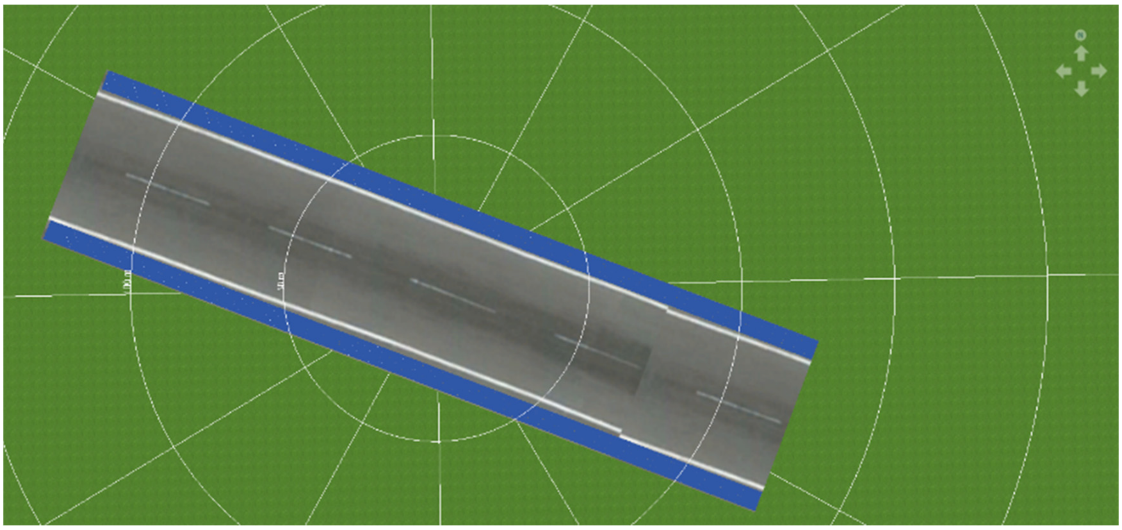


Figure 3. PVSol 3D simulation.

Figure 3 presents the overlay of solar panels using the space between the airport pavement's limit line and the referred pavement's physical end. This software process allowed a detailed understanding and quantification of the allowance of PV panels. By extrapolating Figure 3, the useful area of the airport will be able to implement 54,360 PV panels for a total of around 6.8 MW_p of installed power. Moreover, by extrapolation, the production value of this renewable energy source is reached and presented in Table 2.

Table 2. Results of the PV installation grid injection and accumulated energy simulation.

Months	Grid Injection (MWh)	Accumulated Energy (MWh)
January	367.10	367.10
February	465.07	832.17
March	719.72	1551.88
April	874.07	2425.95
May	1087.74	3513.69
June	1056.07	4569.77
July	1118.22	5687.98
August	1037.83	6725.81
September	826.06	7551.87
October	600.16	8152.03
November	396.77	8548.80
December	334.28	8883.08

The grid injection values from Table 2 are presented in graphical form in Figure 4.

Based on the cost of the Normandy installation, performed by Colas [7], with a total cost of EUR 5 M to implement 2800 PV panels, a cost of 14.29 EUR/Wp or 2588 EUR/m^2 will be further considered in this study to be further compared. It should be noted that this is only a reference value for a 2016 installation, with emerging technology at the time, the cost of which may have reduced in recent years. The selection of the panels consisted of existing devices that provide enough technical information for simulation; nevertheless, there are more suppliers on the market.

In contrast, Correia and Ferreira [1] also state that Smart Road by Qilu Transportation Development Group Co., has a 5875 m^2 installation in Jinan, Shadong Province, which cost EUR 2.365 M [26], giving 402 EUR/m^2 [27]. Sun et al. [8] referred that it was impossible to confirm the previous value on a cost per PV nominal power due to the lack of information; in this case, panel dimensions. Besides the mechanical information not provided by Shandong Pavenergy, the Smart Road PV panel producer, not enough data are provided to simulate the PV system in the selected case study, but the cost will be used to evaluate a lower cost solution.

Based on the previous assumptions, following the price of Colas [7], installing PV panels at this facility would cost a total of EUR 97.071 M.

In summary, the study would result in the data presented in Table 3.

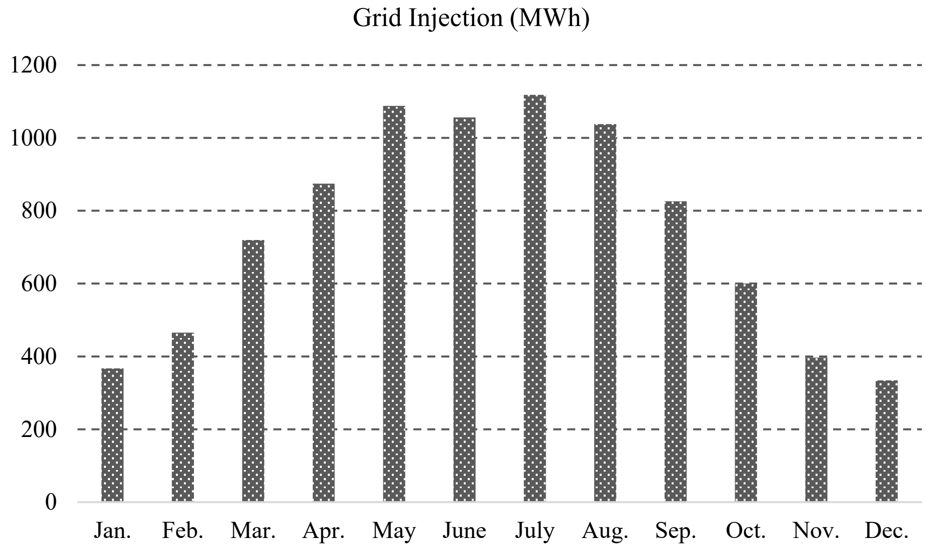


Figure 4. Simulated monthly production.

Table 3. Simulation results.

Simulation Results	
Local	Nordela, Ponta Delgada, Portugal
Target area	47,293 m^2
Weather database	MEOTEOSIM (Ponta Delgada [1951–2010])
PV panels	Wattway 125 W_p (2019)
Inverter	Hoymiles MI-1000
Cable loss	2%
Annual production	8883.08 MWh
Gross estimation	97.071 EUR M

4. Economic Analysis

The analysis continues with the evaluation of CO_2 cost, a fact that could be a target for investment not only by aviation operators following the CORSIA program but also to assist into the national and European objectives to achieve reduction targets for this greenhouse gas emission. Another evaluation to be considered will be the Levelized Cost of Energy (LCOE) to understand the cost of adopting this technology.

Since it is impossible to know the exact cost details of the solution presented in this document, especially if the base value that served as reference already gives the installation, operation, and maintenance costs, for a useful life of 25 years, this value will be used as the total value of the solution. Using the values offered by the manufacturers of standard photovoltaic panels as the valuable life, which this solution would fit into because, in this configuration, the photovoltaic panels would not be subject to traffic usage and airport space safety.

Based on the type of installation and space, we would avoid breakage, thunderstorm damage and leaf mold problems, as mentioned by Correia and Ferreira [1]. Another positive factor is the air expelled by turbines or aircraft propellers that would clean the panels and thus increase the efficiency of photovoltaic panels. The installation cost is sedimented as the technology becomes financially more economical with maturity and economy of scale at a future installation date and size of the installation analyzed here.

Although the equipment supplier does not describe the annual degradation rate of the solar cells, this analysis uses the value of 1% [28,29], and the discount rate is assumed to be 4 [29,30], resulting in the following calculation formula:

$$LCOE = \frac{Installation\ Cost}{\sum_{t=0}^{N-1} \frac{E_p(1-d)^t}{(1+r)^t}} \tag{7}$$

where:
$LCOE$ = Levelized Cost of Energy (EUR/MWh);
$Installation\ Cost$ = Installation Cost (EUR);
N = System lifetime (years);E_p = Energy production in a given year (MWh);
d = Discount rate (%);
r = Solar cell degradation rate (%).

Although the electroproduction system on the island of S. Miguel already uses renewable energy sources, electricity production is mainly obtained via fossil fuel, with fuel oil being the most consumed non-renewable raw material, reaching an annual average of 60% [31]. In addition to fuel oil, diesel is used for electricity production on the island. The region where the island of S. Miguel is located, the autonomous region of the Azores, is supported by the recovery and resilience plan that makes available up to EUR 116 M for energy transition up to 2029 [32].

The energy produced by the proposed system is intended to assist the production of electricity from renewable energy sources by reducing the use of non-renewable primary sources. The following table summarizes the differences between the various energy sources.

The following analysis addresses the compensation for CO_2 emissions by the following formulation:

$$LCOE' = LCOE + CO_{2_{GHG}} \times GHG_{cost} \tag{8}$$

where:
$LCOE'$ = Levelized Cost of Energy, CO_2 compensated (EUR/MWh);
$LCOE$ = Levelized Cost of Energy (EUR/MWh);
$CO_{2_{GHG}}$ = CO_2 equivalent of greenhouse gas source (tCO_2eq/MWh);
GHG_{cost} = Greenhouse gas compensation (EUR/tCO_2).

The Portuguese environmental agency presents a cost for CO_2 compensation of 25.2 EUR/tCO_2 [33], but the Azores electric utilities company (EDA) budget presented a forecast for the purchase of CO_2 emission allowances of 69.38 EUR/tCO_2 [31], a value that will serve as the GHG_{cost} for this study. The Portuguese environmental agency also says that the cost of CO_2 offsetting by the value of renewable energy sources is null.

It is also analyzed a cheaper product, the Smart Road, which assuming the same installation power that Wattway, with the Jinan (Shandong Province) installation, cost [1,27], completes and summarizes the following table.

By analyzing Table 4, the acquisition of the Pavement PV produced by Wattway generates an LCOE about five times higher than similar existing systems in the electroproduction system on the island of S. Miguel. However, if it is possible to confirm the technical aspects of the same design provided by Smart Road, the system fully fits and is comparable with the existing system compared to current PV technology. Table 4 is calculated with a capital expenditure (CAPEX) of EUR 97 M for the installation based on Wattway and EUR 19 M if the installation is based on the Smart Road product.

Adopting the Pavement PV system would reduce the acquisition of 6112 CO_2 emission licenses (or a reduction of 6.11 tons of CO_2), based on producing electric energy by fuel oil. Furthermore, it would mean a reduction of 3.2% of fuel oil purchased, the primary electric power resource, which is non-renewable.

Table 4. LCOE and LCOE′ according to the technologies on S. Miguel Island.

Type of Source	Technology	LCOE (EUR/MWh)	CO_2 Offsetting (tCO_2eq/MWh)	LCOE′ (EUR/MWh)	Production (MWh)
Non-renewable	Fuel oil	0.11 [31]	0.688 [33]	48	272,359 [31]
	Diesel	0.234 [31]	0.733 [33]	51	78 [31]
Renewable (current technologies)	Geothermal	102 [31]	0 [33]	102	144,864 [31]
	Hydroelectric	102 [31]	0 [33]	102	23,622 [31]
	Wind	116 [31]	0 [33]	116	18,501 [31]
	PV (SEPA+SENVA * [1])	129 + 165 [31]	0 [33]	129 + 165	306 + 20 [31]
Renewable (new technology)	Pavement PV (Wattway)	727	0 [33]	727	8883.08
	Pavement PV (Smart Road)	143	0 [33]	143	8883.08

* [1]—Different types of contracts: SEPA = Public Service Electrical System; SENVA = Non-binding Electric System.

Additionally, adopting the system would allow the island electricity company to move away from the volatility of the fossil fuel supply markets and the fluctuation of the CO_2 compensation price. The system would also help the country on its way to reducing carbon emissions.

Hu et al. [29] conducted a similar study by adding rehabilitation costs to the panels. This study, because the panels would only use a non-circulated area, would not have such an impact on the need to rehabilitate them. Thus, a contrast is made between the current applications of equipment in possible solutions to fit the new technologies.

5. Conclusions

This article presents the formulation for calculating the energy produced by photovoltaic (PV) panels that require data which product manufactures do not provide, meaning the production values were achieved using simulation software.

In this analysis, the airport of S. Miguel Island, the largest island in Portugal, was chosen. Due to its isolation and local resources, it uses fossil fuels to supply electricity. The fossil fuels on this island correspond to 60% of the electric energy production.

Using the airport pavement edge would not affect the aircraft, people, and cargo since the areas around the runways and taxiways would not be used, so the aircraft would never run over the PV panels in regular operations. Due to its nature, the airport infrastructure would offer protection from the climate events and damage by humans, and the circulation of the aircraft would clean the debris accumulated on the surface of the panels.

With the use of the airport pavement edge, it would be possible to produce about 9 GWh of electric energy, which would represent 2% of the island's electric energy production, a 3.3% reduction in fossil fuel consumption and avoid more than six tons of CO_2 emissions per year.

The economic analysis compares this technology's use against other existing technologies, concluding that the solution presented by Colas (Wattway) generates a Levelized Cost of Energy (LCOE) of about five times more compared to similar technology. However, Qilu Transportation Group Co. (Smart Road) presents a product that, financially, can produce an LCOE that is comparable to existing technologies.

This analysis presents the contrast of emerging technologies in structures not yet mentioned, such as airport pavements, which are capable of supplying local electrical needs in a financial framework. Besides the regional framework, the benefits include meeting national and European goals in the energy transition to renewable energy sources. In addition to producing needed electrical power, this solution can address the CORSIA program, as it is implemented in a civil aviation infrastructure, offsetting the industry's CO_2 footprint.

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