JJMIE

Volume 18, Number 3, September. 2024
ISSN 1995-6665
Pages 601- 610
https://doi.org/10.59038/jjmie/180313
Editor-in-Chief: Prof. Ali M. Jawarneh

Jordan Journal of Mechanical and Industrial Engineering

Partial Shading Effect on Road-Integrated Photovoltaic Systems

Sarah Rajab[1], Bart Pieters[2], Ahmed Abu Hanieh[1,*]

[1]*Birzeit University, Palestine*
[2] *Julich forchungszentrum, Germany*

Received 16 May 2024 *Accepted 14 Jun 2024*

Abstract

Partial shading of Photovoltaic (PV) system is commonly observed in outdoor field conditions specially in the Road-Integrated Photovoltaic systems. The non-uniform illumination causes mismatch in the electrical output between the cells, which results in an instantaneous effect on power generated and a long-term effect on reliability, it also causes hotspot issues. The objective of this work is to study the partial shading effect on the Road-Integrated PV (RIPV) cells and the soiling model effect under the active and inactive states of Multilevel Bypass (MLB) diodes. In this work, an electrical Simulation Program with Integrated Circuit Emphasis (Ng-SPICE) simulation model has been developed using irradiance model data. This data was collected using a Digital Elevation Model (DEM) called Light Resolution Light detection and Ranging (LidAR). The model was simulated using the Simple Sky Dome Projector (SSDP) software to analyze the impact of different shading conditions and study the effect of MLB diodes on the partial shading RIPV modules and the effect of MLB diodes in the soiling model.

Keywords: Road-Integrated PV; Partial shading; Soiling; Multi-Level Bypass diode; SPICE; Digital Elevation Model.

Nomenclature

Voc: Voltage Open Circuit

Isc: Short Circuit Current

Vmppt: Voltage at Maximum Power Point Tracking

Imppt: Current at Maximum Power Point Tracking

PV: Photovoltaic

RIPV: Road-Integrated Photovoltaic

MLBD: Multi-Level Bypass Diode

Pmppt: Power at Maximum Power Point Tracking

Iph : Photo-current,

Is : Saturation current of diode dependants of temperature

q : Charge of electron = 1.602.10-19C,

K : Boltzmann Constant = 1.381.10-23J/K,

*F :*Conversion factor of

T : Cell Temperature in °K.

*Eg :*Bandgap.

1. Introduction

Using Photovoltaic (PV) modules to generate electricity is known worldwide and widely spread in Middle Eastern and Mediterranean countries and is still used widely as well in European countries like Germany. PV grids are clean source of energy and can be installed in different shapes; on-ground, roof-top or road-integrated. On-ground and roof-top face the problems of dust and dirt and need to be cleaned from time to time. Road- integrated PV modules suffer from the problems of soiling and partial shading due to soil and tree leaves. This study tackles the obstacles facing Road-Integrated PV modules (RIPV) caused by soil coverage and partial shading showing the influence on produced power in each case. Multi-level Bypass (MLB) diodes are introduced here as a solution to these problems and simulation results are shown for different cases.

1.1. Renewable Energy and Photovoltaic (PV) Projects

The usage of photovoltaic (PV) is increasing rapidly worldwide and the solar energy generation has increased by an average of 41% per year since 2009, with a total of 295 GW installed worldwide as of the end of 2022 [1]. There are many examples of integrated applications like Building Integrated PV (BIPV), and Vehicle-Integrated PV (VIPV)[2]. But this increase in implementation is accompanied with many requirements to use RIPV as a road, such as durability and safety to be able to stand under all weather conditions of the road surface[3]. Some research groups concentrated on vehicle-integrated PV panels like [4] to extend the driving range and reduce the charging needs in electric vehicles. While others focused on power

* Corresponding author e-mail: ahanieh@birzeit.edu.

flow using solar road generation coupled with traffic flow [5].

The world delves into the imperative shift toward clean energy as a pivotal goal in the 21st century science and technology. It highlights the environmental concerns stemming from fossil fuel consumption, emphasizing the role of PV solar energy in curbing CO2 emissions[6]. The affordability of PV modules is underscored as an economically sustainable and environmentally friendly solution for investment.

The characteristics of PV energy, detailing its conversion into electricity using solar PV modules are discussed in [7]. The reference shows the advantages of PV projects, including their ability to operate independently or integrate with the grid. It also presents the global growth of PV solar energy.

1.2. Road-Integrated Photovoltaic systems RIPV

The concept and challenges of Road-Integrated Photovoltaic (RIPV) is an integrated photovoltaic application. RIPV involves embedding solar cells within the road surface to harness solar energy while maintaining road functionality. Challenges include durability, safety, and transparency for energy yield. Although various RIPV concepts have been explored while large-scale application is not yet feasible.

The concept of integrated PV applications, focusing on RIPV is a challenging application where solar cells are integrated into road surfaces, the concept was depicted by Dezfooli et al. [8]. It discusses the design considerations, such as transparency, durability, and safety, along with the modular structure of RIPV [7]. Sinan in [8]reviewed solar road developments, highlighting the SolarRoad pilot project launched in Krommenie, Netherlands, in 2014[9]. The Wattway project in France, initiated by Colas and INES in 2016, marked the country's first solar road designed for vehicle use.

It was introduced by Li et al. in 2009[7] that RIPV modules are modular and consist of three layers: a transparent top layer, a middle functional layer housing solar cells, and a bottom protective layer. The transparent layer requires mechanical strength, anti-slip properties, and high transmittance for sunlight exposure. Materials include tempered glass, reinforced resins, and glass aggregate. Tempered glass is preferred for long-term stability, with potential skid resistance improvements.

The middle layer contains solar cells, categorized into solid and hollow models. Solid structures are favored due to their resilience against damage and moisture penetration. The last layer serves to transfer loads, protect solar cells, seal modules, and use materials like tempered glass, concrete, resin, and polymer substrate. Tempered glass and recycled materials are often chosen for their stability and ecological impact, respectively. Overall, RIPV aims to integrate solar cells seamlessly into road structures, but challenges persist, necessitating further research for widespread implementation[7].

1.3. Partial Shading, Soiling Factor and Bypass Diodes

This section addresses factors influencing the outdoor performance of photovoltaic (PV) modules, particularly Road Integrated Photovoltaic (RIPV). Various elements, including material degradation, solar irradiance, thermal loss, ohmic resistances, fill-factor, shading, soiling, potential induced degradation, tilt angle and impact module performance [8]. The focus is on two significant challenges: partial shading and soiling disturbance.

Partial shading[9] occurs when certain areas of a PV array are shaded, reducing power and affecting the performance ratio (PR). This shading leads to a voltage drop in shaded PV cells, potentially causing hot spots and compromising the system's proper functioning. To mitigate this issue, bypass diodes are commonly installed in antiparallel with PV module cells. These diodes bypass the current of reverse-polarized cells, allowing the remaining cells to operate freely.

Multi-level bypass diodes (MLBD) represent an advanced approach, introducing different paths for module current. When a cell is shaded, the current path changes to pass through the bypass diode, maintaining total current and minimizing losses. However, the number of bypass diodes in the path affects voltage reverse bias and, consequently, power generation losses [10].

Soiling[11], the accumulation of dust[12], dirt, and contaminants on PV modules, is another challenge. Dust, with particles less than 500 μm in diameter, affects module performance based on various factors, including dust properties, weather conditions, location, module tilt angle, surface finish, and wind speed [12]. Permanent soiling can occur due to humidity condensate, leading to annual power losses of 5-17% or more[13]. Soiling impacts are higher in dusty or desert areas but lower in regions with frequent rains and rural roads [14]. Rooftop PV systems generally experience fewer soiling losses compared to ground-mounted systems.

The main factors influencing outdoor PV module performance, particularly partial shading and soiling are studied by Guo et al. in [9]. It details the adverse effects of partial shading on power generation [15],the dust is classified into two categories: soft and hard soiling [11], While the concept of bypass diodes to mitigate these effects is introduced in [12]. The importance of light intensity in PV power generation is explained, highlighting the impact of shading caused by obstacles.

Other researchers worked on increasing the power taken from PV cells to reduce the number of needed cells using the bond graph control [16]. Others used optima; a design technique to improve the lifecycle and payback period of PV cells in passive residential buildings and many other applications [17-20].

The economic performance of solar PV panels and cells was tackled by many researchers in the MENA region specially in Jordan as can be seen in the references [21-25]. The researchers concentrated on the measurement of power and efficiency of electric to thermal process due to the wide range of applications for PV panels. Photovoltaic panels are used in a hybrid mode with wind energy to increase the performance and power output as discussed in [26].

In summary, this paper provides a comprehensive overview of the motivation behind transitioning to renewable energy, the prominence of PV solar projects, and challenges faced by integrated PV applications like RIPV, and the influence of partial shading and soiling on PV module performance. It sets the stage for further exploration of these topics in subsequent sections.

2. Methodology and simulation

The section discusses the main challenges in RIPV that come from the local environment and the effect it has on the modules performance, focusing on the partial shading impact and the soiling effect. The study is based on a (0.304 kWp) RIPV solar project at the Julich research center in Germany, delving into the impact of partial shading, soiling, and the addition of bypass diodes on RIPV simulation, trying to mitigate the losses.

2.1. RIPV Performance Simulation

The RIPV system under investigation is the Solmove RIPV, a smart street PV panel with eight modules, each comprising 36 series-connected cells, as shown in Figure 1. The module structure incorporates a transparent top layer for solar irradiance, a silicon wafer core insulated with bitumen adhesive, and a bottom layer of compressed sand with gravel frost protection. The study utilizes Digital Elevation Model (DEM) data, specifically high-resolution Light Detection and Ranging (LiDAR) data, to detail local shading conditions and topography, as shown in Figure 2. This data is crucial for accurate simulation and performance analysis [15].

The research leverages tools like the Simple Sky Dome Projector (SSDP) software program, implementing the Perez "All Weather Sky Model" (AWSM) to model irradiance [16]. Unlike other solutions, SSDP avoids the overhead associated with large grid approaches, catering specifically to RIPV applications. The model considers isotropic sky approximations for diffuse irradiance components, addressing non-isotropic conditions under various weather scenarios.

The simulation involves time, coordinates, sun location, and earth distance computations, incorporating GHI and DHI values. The SSDP program projects the sky on a tilted surface, considering solar position, air temperature, and pressure. The research extends its focus to investigate different RIPV concepts, particularly regarding shading losses and degradation. Techniques like SSDP help compute irradiance for shaded modules, enabling the calculation of photocurrent and mismatch losses, as shown in Figure 3.

In summary, the study adopts a comprehensive approach, utilizing advanced technologies and models to analyze the performance of RIPV solar modules under varying conditions, contributing valuable insights to the field of integrated photovoltaics.

2.2. Concept and algorithm of Modelling MLB diodes:

This section details the application of SPICE (Simulation Program with Integrated Circuit Emphasis) modeling to investigate the performance of Road Integrated Photovoltaic (RIPV) Solmove crystalline wafer cells, specifically focusing on shade tolerance. The SPICE model serves as a mathematical representation of electronic components, offering a means to design and optimize circuits, including those involving diodes.

The study aligns the SPICE model with lab data, as shown in Table 1. The characteristic of the solmove modules, derived from experimental lab tests on RIPV Solmove modules. The output data from the Simple Sky Dome Projector (SSDP) binary file is utilized, providing information on Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DHI), and module temperature. This data serves as input for the SPICE simulation.

Figure 1. Silicon Wafer RIPV with capacity (0.304 kWp) ,Solmove (38 Wp),8 modules installed in series

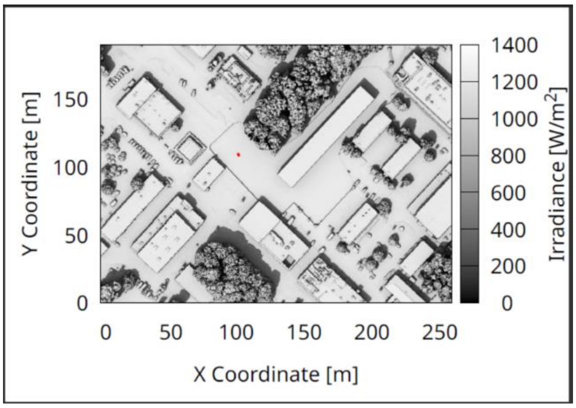


Figure 2. The image of Irradiance and shading for the staff around with high resolution, the red square presents the RIPV modules

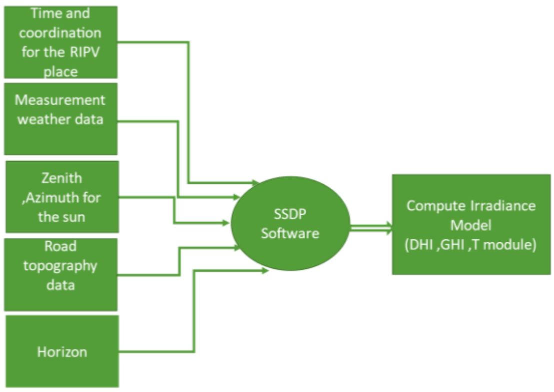


Figure 3. PV performance Modeling using SSDP software taking into account the DEM.

Table 1. The datasheet for the Solmove modules, Crystalline Wafer Silicon modules.

Characteristics	Value
V oc	22.5 V
I sc	2.09 A
P mpp	37.8 w
V mpp	18.9v
I mpp	2 A

Electrical design optimization for shade-tolerant RIPV involves integrating and modeling the MLB diode[10] concept through SPICE simulations. Various bypass diode configurations are implemented to assess their impact on the RIPV system under different shading conditions. The section includes the characteristics of Solmove modules and introduces the diode equation for simulating solar cells in SPICE.

The diode equation considers photocurrent (Iph) based on light conditions, with calculations under Standard Test Condition (STC) conditions. The parameters used in the SPICE simulation model, including saturation current (I0), ideality factor (N), series resistor (Rs), shunt resistor (Rsh), and conversion factor (F), are outlined in Table 2.

Table 2. Characteristic parameters used in the SPICE simulation model for the solar cell.

Abbreviation	Value	Parameter
I0	0.728*10-9	Saturation current
N	1	Ideality factor
Rs	.015	Series resistor
Rsh	718.50	Shunt resistor
F	.002130	Conversion factor
Eg	1.1230	Bandgap

The simulation involves calculating mean power (P_{mean}) and energy yield (E) for the module based on irradiance values.Also explains the process of obtaining POA irradiance models for various weather conditions and shading from SSDP software. These models are then used to calculate parameters for non-shaded, shaded, and homogeneous cases, with the data entered into the SPICE simulation for analysis.

By measuring the irradiance values every 5 minutes over the course of a year and calculating the average current for each cell using ratio and proportion in simulation, our model does not accurately reflect real-world conditions. This is because the Renewable Energy Integrated Photovoltaic (RIPV) system is not actively generating electricity during the testing phase. Instead, it is undergoing evaluation to determine its robustness and ability to withstand various weather conditions specially it’s the first project in Germany.

To mitigate partial shading losses, various bypass diode configurations are explored using the Ng-SPICE software. The study assumes different designs for single-stage and MLB diodes, analyzing their effects on yield energy and their ability to mitigate partial shading losses.

2.3. Soiling Model

The soiling model is introduced to assess the impact of dirt and particles on the photocurrent of RIPVcells. The model assumes the presence of both small and large particles distributed across the cells, resulting in approximately 365 distinct soiling patterns redistributed daily. While this may not perfectly replicate real-world scenarios, it serves as a foundation for studying effects on current and power generation. The primary goal is to determine if the implementation of bypass diodes can mitigate and reduce these losses while safeguarding the RIPV system from potential damage.

The simulation script involves fixed-average irradiance simulations and integrates soiling distributions. Two scenarios are considered: one with large particles (.05 m) having a dirt coverage factor (CF) of 10%, and another with small particles (.01 m) also having a dirt CF of 10% of the panel area. These simulations allow for the assessment of generated current and power under soiling conditions, providing insights into the potential benefits of using bypass diodes to mitigate losses and preserve RIPV system performance.

Figure 4 illustrates the assumption model of small particles (R=.01 m) distributed over the modules, representing small soil or dirt particles that may adhere to the RIPV. The simulation is conducted initially without bypass diodes to study power losses and their impact on the Performance Ratio (PR) of the RIPV. Subsequently, the simulation is performed with the inclusion of MLB diodes to analyze their potential in mitigating losses and protecting the RIPV from hot spot issues.

Similarly, Figure 5 presents the assumption model of large particles (.05 m) radius distributed over the RIPV modules, representing leaves or larger dirt particles. The simulation is conducted without bypass diodes initially to study power losses and their effect on the PR of the RIPV. It is followed by a simulation with the inclusion of bypass diodes to analyze their effectiveness in mitigating losses and protecting the PV system from hot spot issues.

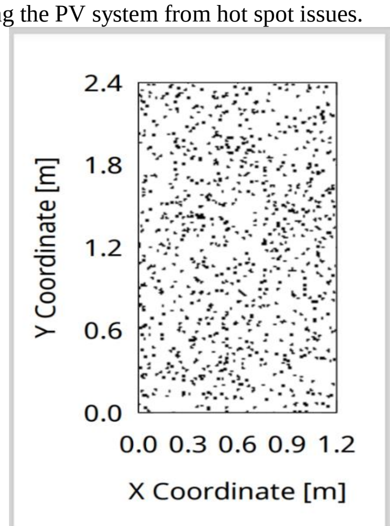


Figure 4. The assumption model of small particles of (0.1m) radius distributed over the modules

3. Results of simulation

In this section, the analysis of data results for the performance of RIPV modules is presented, focusing on the simulation and modeling of MLB diodes, considering partial shading and soiling effects with various particle assumptions.

3.1. Partial Shading Effect Data Analysis

The RIPV modules are inherently surrounded by shading objects, leading to unavoidable partial shading issues. This effect is particularly prominent in winter due to the low sun elevation. The data analysis focuses on PV performance and power yield during January 2015 to calculate the cells' parameters, power, and energy yield.

Figure 6 highlights the severe partial shading impact in December, the worst period in Germany. A noticeable power decrease occurs between 11:00 and 15:30, with a 33% reduction for shaded modules (60 W to 40 W) and a 26% reduction for homogenous modules (60 W to 44 W). The mismatch loss is calculated at 7%, emphasizing the critical need to address this significant issue.

The data analysis provides insights into the varying effects of partial shading on RIPV performance throughout the year, underlining the importance of understanding and mitigating these losses for optimal system efficiency.

This comprehensive comparison underscores the significant influence of environmental factors on solar cell efficiency. The enhanced visualization with bold, enlarged axis labels, and a clear legend provides an intuitive understanding of the data, facilitating the assessment of different operational scenarios. These findings are crucial for optimizing the placement and maintenance of solar panels to maximize their energy output and overall efficiency.

3.2. Modeling and Simulation of adding MLB diodes Configuration in the Soiling Assumptions and the Standard Case.

In an effort to mitigate partial shading effects and prevent hotspot issues, the study employs the single-stage bypass diode and MLB diodes method. Various configuration designs for MLB diodes are considered, including Tier 1 with one diode per module, Tier 2 with four diodes in the string, and Tier 3 with nine diodes in the string. Different design combinations (Design A, B, C and D) are explored for optimal performance.

Figure7 illustrates the MLB diodes with varied configuration designs, showcasing the different tiers and design combinations. Despite the anticipation that MLB diodes would alleviate partial shading losses, SPICE simulations.

Figure 8 : highlights the annual power generation for all modules across varied weather models under standard conditions. The power generated from the RIPV modules throughout the year, recorded every 5 minutes, shows the best production in June, with the lowest production in shaded modules. The addition of MLB diodes has a limited effect on power generation.

Table 3 provides the yield energy for different weather models and MLB diode configurations, emphasizing that the best energy yield is observed for MLB diode design D (1,4,9).

In the comprehensive analysis, shading loss is a substantial factor, contributing to 13% of the total energy loss. Mismatch loss accounts for an additional 1%, while minimum shading loss stands at approximately 0.88%. These findings underscore the significant influence of shading effects on productivity losses.

The study acknowledges the potential debate ability of the realistic nature of the (R=.05 m) distribution, emphasizing the inherent complexity of real-life scenarios. Although significant losses due to non-uniform soiling patterns may not be widespread, they can be observed in road applications that deviate from the norm, particularly in poorly constructed roads with inadequate drainage or areas with a significant presence of fallen leaves. This correlation is conceptually aligned with the generation of non-uniform soiling patterns.

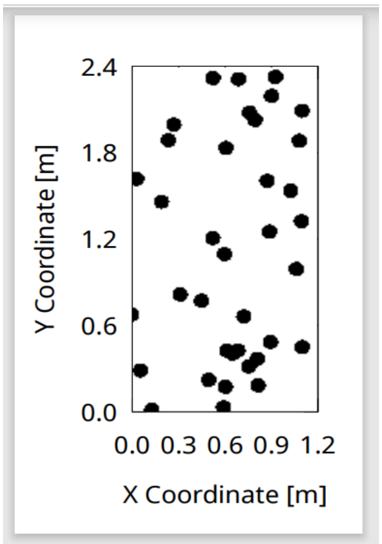


Figure 5. The assumption model of big particles (.05m) radius distributed over the RIPVmodules

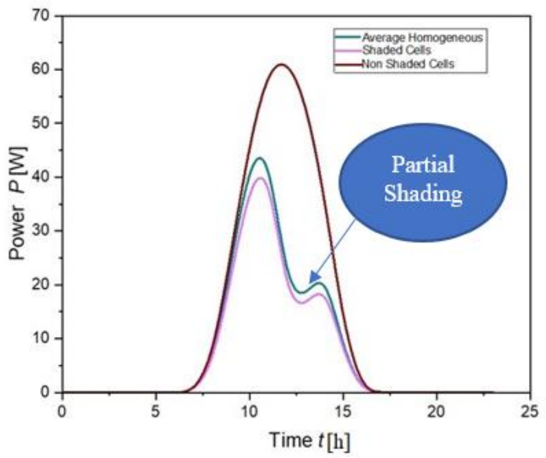
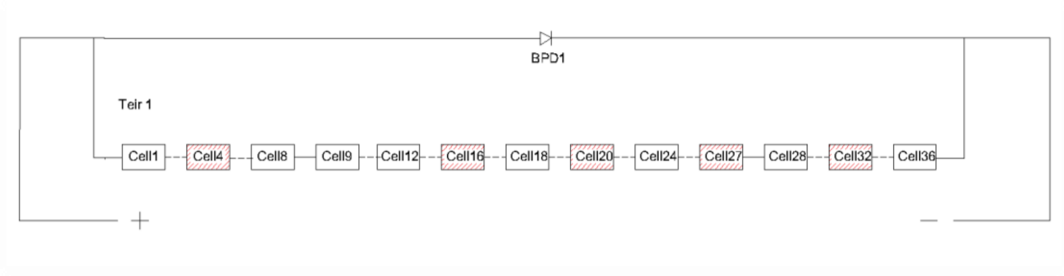
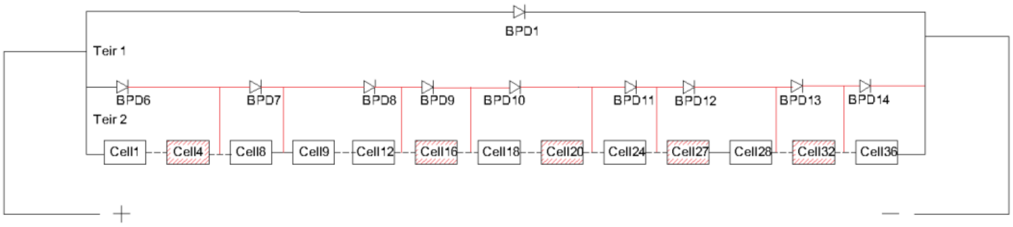


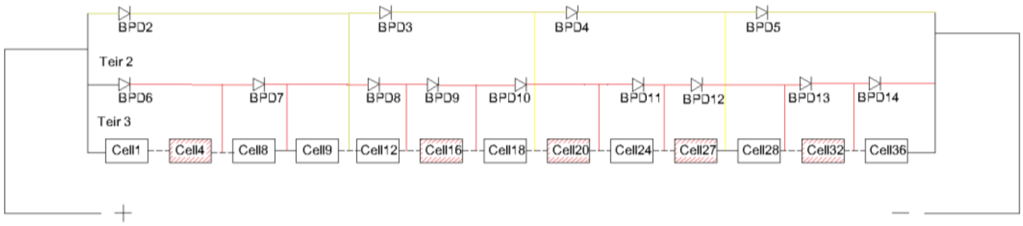
Figure 6. Partial Shading Impact on the Road Integrated Photovoltaic (RIPV) System in December 2015.



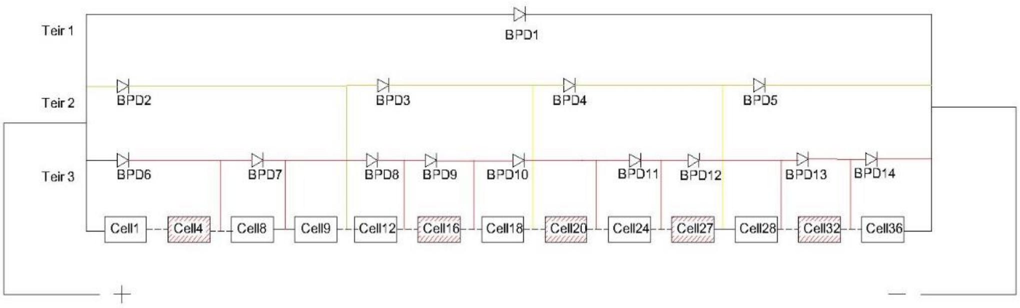
Design A



Design B



Design C



Design D

Figure 7. MLB diodes with varied configuration designs A, B, C, D consequently.

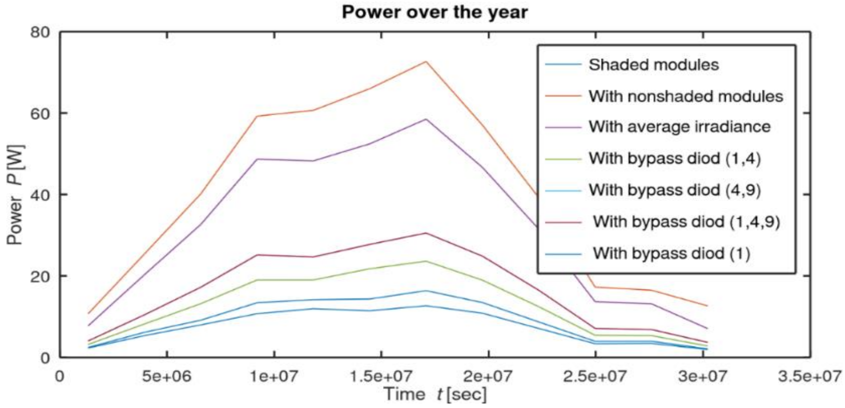


Figure 8. Annual power generation for all models

Table 3. The Yield Energy yield for all the weather models and different configuration of MLB diodes for the 8 modules (Standard Case) without soiling factor.

Weather models & Configurations (Standard Case)	Energy yield (Wh)
Shaded, Ys	302,465.99
Avg-homogenous,Yh	306,930.90
Non-shaded,Y ns	348,168.39
Design A	304,391.80
Design B	305,059.55
Design C	305,079.01
Design D	305,173.08

Table 4 and Table 5 depict the implementation of MLB diodes in the case of (R=0.05 m) for different configurations (A, B, C, D). The addition of MLB diodes results in substantial increases in energy yield compared to shaded energy yield. For example, Design (A) shows a 21% increase, Design (B) exhibits a 72% increase, and Design (C) and Design (D) show even more significant gains of 123% and 79,937.19 Wh, respectively. These improvements are equivalent to adding additional cells to enhance overall production, highlighting the effectiveness of incorporating MLB diodes in mitigating losses associated with large particle assumptions. Figure 10 provides a summarized view of the energy yields generated from all modules for different weather models and MLB diode configurations, emphasizing the positive impact of MLB diodes on energy production.

Table 4. Yield energy for implementing MLB in different configurations

Weather models	**Yield Energy (Wh)-Standard Case**	**Yield Energy (Wh) with soiling (CFF= 10 %,R=.01 m)**	**Yield Energy (Wh) with soiling (CFF= 10 %,R=.05m)**
Shaded	302,465.99	247,146.35	65,061.94
Avg-homogenous	306,930.90	277,229.66	277,544.02
Non-shaded	348,168.39	348,168.39	348,168.39
A	304,391.80	248,741.15	78,944.10
B	305,059.55	251,040.15	111,581.54
C	305,079.01	253,611.84	144,952.52
D	305,173.08	253,685.20	144,999.13

Table 5. The energy yield gain as a result of adding MLB diodes configuration designs.

Bypass configuration design	Gained yield energy (Wh) - Standard Case	Gained yield energy (Wh) - soiling (CFF=10%,R=.01 m)	Gained yeild energy (Wh) -soiling (CFF=10% ,R=.05m)
A	1,925.81	1,594.80	13,882.16
B	2,593.56	3,893.80	46,519.59
C	2,613.02	6,465.49	79,890.58
D	2,707.09	6,538.85	79,937.19

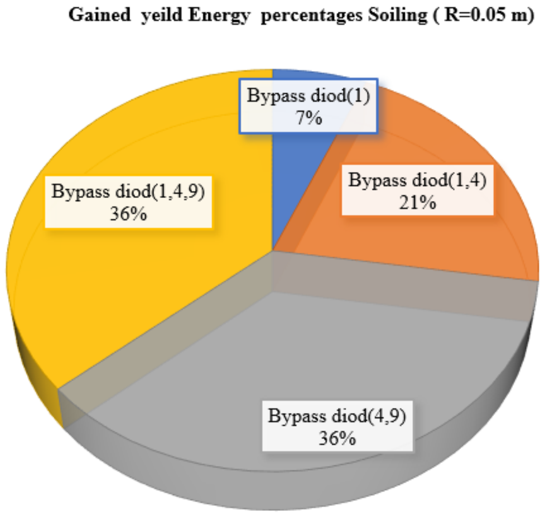


Figure 9. The acquired energy yield in the presence of soiling conditions (0.05 m) was assessed by introducing distinct designs of MLB diodes denoted as A, B, C, and D.

In this novel, the performance of solar cells was analyzed under various conditions by plotting I-V curves [18]. The conditions examined include shaded and non-shaded cells, cells under average irradiance, and cells affected by different levels of soiling, also with different levels of BPD (4,9), (1,4), (1,4,9), and (1). The data was processed to calculate the average short-circuit current (Isc), open-circuit voltage (Voc), voltage at maximum power point (Vmppt), and current at maximum power point (Imppt) for each condition. These average values were then used to interpolate the I-V curves as shown in Fig.10

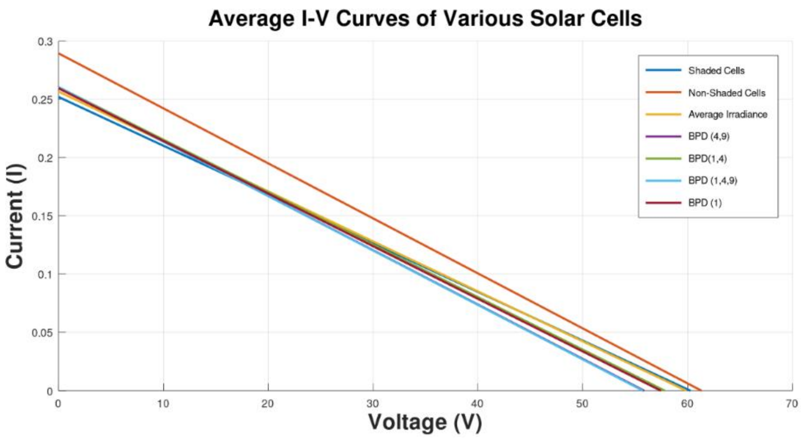


Figure 10 . The IV characteristic curve over the RIPV with different weather conditions in the standard case.

The resulting plot, as shown in Figure 11, displays the I-V characteristics of solar cells under these diverse conditions with soiling factor R=0.01m. Notably, the curves illustrate how shading negatively impact the electrical performance of the solar cells, evidenced by reduced current and voltage values. The non-shaded cells exhibit the highest performance, with the lowest one in the shaded cells

Figure 12 presents the I-V characteristics of solar cells under various conditions with a soiling factor ofR=0.05m. The curves clearly demonstrate the adverse impact of shading on the electrical performance of the solar cells, indicated by decreased current and voltage values. The non-shaded cells achieve the highest performance, while the shaded cells show the lowest. Additionally, the beneficial effect of bypass diodes on the IV curve is evident, particularly at stages 1, 4, and 9.

4. Cost Analysis

This thesis focused on Bypass Diodes and Shade Tolerance of Road Integrated Photovoltaic (RIPV) systems, a comprehensive cost analysis was conducted to determine the economic viability and practical feasibility of integrating bypass diodes and shade tolerance features. This analysis plays a crucial role in evaluating the return on investment, optimizing technology deployment, ensuring compliance with financial regulations, and contributing to the overall success and market competitiveness of RIPV systems.

The cost components were identified, encompassing initial costs such as solar panels, inverters, AC & DC cables, accessories, and bypass diodes. Operational and maintenance costs were highlighted, emphasizing the importance of systematic cleaning, monitoring, and maintenance procedures for the efficiency and longevity of the solar system.

The study then performed a key financial metrics analysis for three scenarios: Standard Case (non-shading), Soiling (R=0.05 m), and Soiling (R=.05 m) with Bypass Diodes (BPD). The results were consolidated in Table 6, providing a comprehensive summary of financial metrics such as Payback Period, Net Present Value (NPV), Internal Rate of Return (IRR), Levelized Cost of Energy (LCoE), and Profit during 25 years. The comparative analysis revealed optimal performance in the Standard Case, while the scenarios involving soiling demonstrated varying economic outcomes, emphasizing the importance of considering these factors in RIPV system planning and implementation.

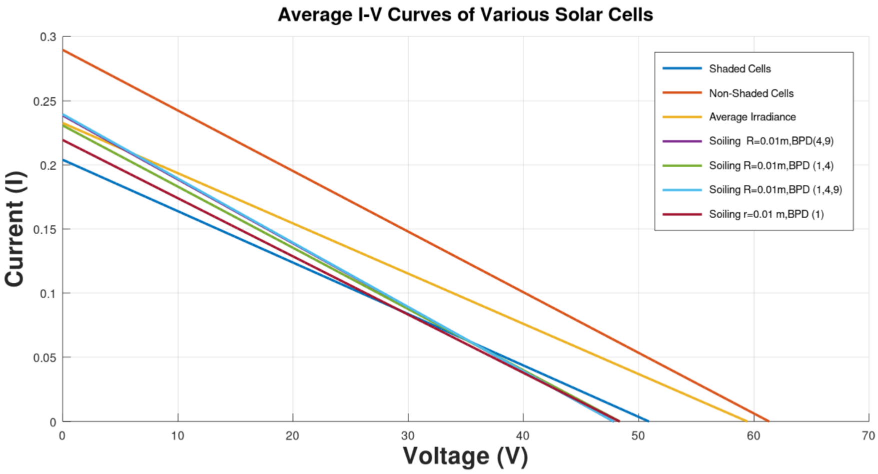


Figure 11. The IV characteristic curve over the RIPV with different weather conditions with soiling effect R=0.01m.

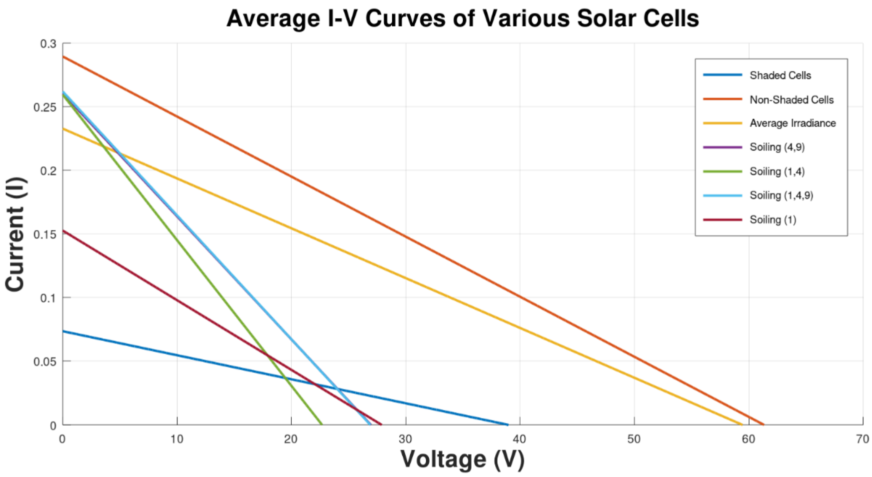


Figure 12. The IV characteristic curve over the RIPV with different weather conditions with soiling effect R=0.05m.

Table 6. Key parameters and financial metrics for three distinct scenarios of a solar project

Item	Standard Case (non-shading)	Soiling (R=.05m)FF = 10 %	Soiling (R=.05m) with BPD, FF=10%
Installed Capacity (kWp)	10	10	10
# of BPD	0	0	3696
# of modules	264		
Power of module(wp)	38		
Yearly (kWh/kWp)	1145	213	477
Initial cost of project ($)	7000	7000	7500
LCoE($/kWh) for (1) kWp	0.1	0.5	0.24
IRR (%)	30.95%	-2.05%	9.15%
NPV return rate ($)	12,939	-5,138	-491
Profit during 25 years ($)	48,605	-1,743	12,088
Payback Period (Year)	3.2	36	10

5. Conclusions and recommendations

This section presents the findings of the study, focusing on the performance coefficient and productivity of Road Integrated Photovoltaic (RIPV) cells, a novel application for solar cells. The study examines the impact of partial shading, a significant challenge faced by RIPV systems. Additionally, it investigates the influence of soil and dust on cell productivity, considering particle sizes of R = 0.01 m and 0.05 m with a 10% fraction factor. The results reveal a substantial energy loss in the presence of larger particles (.05 m), emphasizing the effectiveness of bypass diodes in significantly improving cell productivity, equivalent to adding 66 cells, thus proving economically viable.

Furthermore, the study emphasizes the potential of incorporating MLB diodes to mitigate power and energy losses caused by partial shading and soiling factors across different scales. The most notable effect is observed with large particles, aligning with the bypass diode concept of creating new paths for the current to minimize losses. The study concludes by reporting on the performance and productivity of RIPV, highlighting its status as the first small-scale project in Germany with a capacity of 0.304 kWp at the Julich Research Center.

The cost analysis study shows that the system becomes completely feasible in the case of soiling where the payback period of the systems is mitigated from 36 years to 10 years.

Acknowledgements

The authors would like to thank the JULICH research center in Germany for giving the opportunity to hold the experimental and simulation processes of this project. This article is based on Master thesis research held in the Master program of Renewable Energy Management at Birzeit University.

References

[1] Solar Power EU, Global Market Outlook For Solar Power: Focus on Southeast Asia, 2023. [Online]. Available: www.solarpowereurope.org

[2] J. Markert, C. Kutter, B. Newman, P. Gebhardt, and M. Heinrich, “Proposal for a safety qualification program for vehicle-integrated PV modules,” Sustainability, vol. 13, no. 23, pp. 1–14, 2021, doi: 10.3390/su132313341.

[3] S. Li, T. Ma, and D. Wang, “Photovoltaic pavement and solar road: A review and perspectives,” Sustainable Energy Technologies and Assessments, vol. 55, no. November 2022, p. 102933, 2023, doi: 10.1016/j.seta.2022.102933.

[4] M. C. Brito, T. Santos, F. Moura, D. Pera, and J. Rocha, “Urban solar potential for vehicle integrated photovoltaics,” Transportation Research Part D: Transport and Environment, vol. 94, 2021, p. 102810, doi: 10.1016/j.trd.2021.102810.

[5] W. Dai, B. Shi, T. Li, H. H. Goh, and J. Li, “Power flow analysis considering solar road generation,” Energy Reports, vol. 8, 2022, pp. 531-536, doi: 10.1016/j.egyr.2022.02.232.

[6] Y. Hamakawa, “Background and Motivation for Thin-Film Solar-Cell Development,” in Thin-Film Solar Cells: Next Generation Photovoltaics and Its Applications, pp. 1–14, 2004, doi: 10.1007/978-3-662-10549-8_1.

[7] Y. Hamakawa, “Background and Motivation for Thin-Film Solar-Cell Development,” in Thin-Film Solar Cells: Next Generation Photovoltaics and Its Applications, pp. 1–14, 2004, doi: 10.1007/978-3-662-10549-8_1.

[8] S. Li, T. Ma, and D. Wang, “Photovoltaic pavement and solar road: A review and perspectives,” Sustainable Energy Technologies and Assessments, vol. 55, no. November 2022, p. 102933, 2023, doi: 10.1016/j.seta.2022.102933.

[9] V. K., “An Overview of Factors Affecting the Performance of Solar PV Systems,” Energy Scan, no. February, pp. 2–8, 2017. [Online]. Available: https://www.researchgate.net/publication/319165448

[10] M. M. Fouad, L. A. Shihata, and E. S. I. Morgan, “An integrated review of factors influencing the performance of photovoltaic panels,” Renewable and Sustainable Energy Reviews, vol. 80, no. July 2016, pp. 1499–1511, 2017, doi: 10.1016/j.rser.2017.05.141.

[11] S. Guo, T. M. Walsh, A. G. Aberle, and M. Peters, “Analysing partial shading of PV modules by circuit modelling,” Conference Record of the IEEE Photovoltaic Specialists Conference, pp. 2957–2960, 2012, doi: 10.1109/PVSC.2012.6318205.

[12] M. K. Mazumder, R. Sharma, A. S. Biris, J. Zhang, C. Calle, and M. Zahn, “Self-cleaning transparent dust shields for protecting solar panels and other devices,” Particulate Science and Technology, vol. 25, no. 1, pp. 5–20, 2007, doi: 10.1080/02726350601146341.

[13] E. Boykiw, “The effect of settling dust in the Arava valley on the performance of solar photovoltaic panels,” Pennsylvania, 2011. [Online]. Available: https://scholar.google.com/scholar?lookup=0&q=+Boykiw+E.+The+effect+of+settling+dust+in+the+Arava+valley+on+the+performance+of+solar+photovoltaic+panels.+Department+of+Environmental+Science+Allegheny+College+Meadville,+Pennsylvania+(April+2011)%3B+2011&hl

[14] S. Ghazi, K. Ip, and A. Sayigh, “Preliminary study of environmental solid particles on solar flat surfaces in the UK,” Energy Procedia, vol. 42, pp. 765–774, 2013, doi: 10.1016/j.egypro.2013.11.080.

[15] Sayyah, M. N. Horenstein, and M. K. Mazumder, “Energy yield loss caused by dust deposition on photovoltaic panels,” Solar Energy, vol. 107, pp. 576–604, 2014, doi: 10.1016/j.solener.2014.05.030.

[16] C. de W., W. G. J. H. M. van S., and B. B. Pannebakker, "Photovoltaics in the shade: one bypass diode per cell revisited," Progress in Photovoltaics: Research and Applications, 2017, doi: 10.1002/pip.2898.

[17] Abd Essalam, B. A. D. O. U. D., and K. H. E. M. L. I. C. H. E. Mabrouk. "Development of a bond graph control maximum power point tracker for photovoltaic: Theoretical and experimental." Jordan Journal of Mechanical and Industrial Engineering, vol. 7, no. 1, 2013.

[18] S. Jaber, and A. Abul Hawa. "Optimal design of PV system in passive residential building in Mediterranean climate." Jordan Journal of Mechanical and Industrial Engineering, vol. 10, no. 1, 2016.

[19] T. Abdelaziz, Dalila Beriberb, and Mohamed Seghir Boucheritb. "Performances of photovoltaic generator multi-level cascade." Jordan Journal of Mechanical and Industrial Engineering vol. 4, no. 1, 2010.

[20] Tarabsheh, Issa Yousef Etier, and Rolf Dr Hanitsch. "Transient Analysis and Output Characteristics of DC Motors Fed by Photovoltaic Systems." Jordan Journal of Mechanical and Industrial Engineering, vol. 4, no. 1, 2010.

[21] Jaber, Jamal O., Mohammad O. Awadi, Ali S. Dalabeeh, and Ibrahim M. Mansour. "Performance and Socioeconomics of 1st Wheeling PV Project Connected to Medium Grid in Jordan." Jordan Journal of Mechanical and Industrial Engineering, Vol.16, no. 4, 2022.

[22] Nijmeh, Salem, Bashar Hammad, Mohammad Al-Abed, and Riad Bani-Khalid. "A Technical and Economic Study of a Photovoltaic-phase Change Material (PV-PCM) System in Jordan." *Jordan Journal of Mechanical and Industrial Engineering,* vol. 14, no. 4, 2020.

[23] Jawarneh, Ali M., Ahmad K. AL-Migdady, Amer K. Ababneh, Hitham M. Tlilan, and Mohammad Tarwaneh. "Measurement and Assessment of Solar Energy in Zarqa Governorate-Jordan." *Jordan Journal of Mechanical and Industrial Engineering,* Vol. 17, no. 4, 2023.

[24] Tashtoush, Ghassan M., and Mohammad A. Alzoubi. "An analysis of the Performance and Economic Feasibility of a Hybrid Solar Cooling System that Combines an Ejector with Vapor Compression Cycles, Powered by a Photovoltaic Thermal (PV/T) Unit." *Jordan Journal of Mechanical and Industrial Engineering, Vol.* 17, no. 1, 2023.

[25] Al-Maghalseh, Maher. "Experimental study to investigate the effect of dust, wind speed and temperature on the PV module performance." *Jordan Journal of Mechanical and Industrial Engineering,* Vol. 12, no. 2, 2018.

[26] Hussein, Nidal. "Greenhouse Gas Emissions Reduction Potential of Jordan's Utility Scale Wind and Solar Projects." *Jordan Journal of Mechanical and Industrial Engineering,* Vol. 10, no. 3, 2016.