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# An Optimization Study of both On-Grid and Off-Grid Solar-Wind-Biomass Hybrid Power Plant in Nakalawaka, Fiji

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***Abstract: Small Island Developing (SID) States mostly faces lack of adequate service of energy due to their large dependency on fossil fuels. Moreover, due to increase in global warming and pollution the scenario has to be changed and these SID States have to switch over to the option of generating energy from Renewable Resources. It is possible to mitigate the problems related to inadequate energy by utilizing the Renewable Energy Resources of those areas. The main aim of this paper is to design both on-grid and off-grid Solar-Wind-Biomass Hybrid Power Plant in Fiji, one of the SID State. The model has been designed and optimized by using HOMER Pro® (Hybrid Optimization of Multiple Energy Resources) software. The optimization result shows that the proposed Hybrid Power Plant can easily serve the fixed portion of the load demand for chosen area in Fiji. Furthermore, the result shows that on-grid connected Solar-Wind-Biomass Hybrid Power Plant is much more profitable than off-grid connected. The area chosen in Fiji is Nakalawaka.***
***Keywords: HOMER Pro®, On-grid, Off-grid, Hybrid Power Plant, Solar PV, Wind Turbine, Biomass Generator.***

## I. INTRODUCTION

At present scenario, the whole world is moving towards renewable energy use due to the increasing air pollution in the environment. Increasing air pollution affects the environment by increasing global warming and also increases health problem. And due to which it is better to locate those places in the world that have high possibility of renewable power generation and use it to for renewable power generation. One such place is Fiji. This type of generation not only promotes pollution free energy but also Fiji can sell this power to other countries for their profit. Fiji is a Small Island Developing (SID) State which comprises of 300 small islands in total and a population nearly about 900,000 as estimated in the year 2016. The net electricity generation as of 2016 by Fiji Electricity Authority is 923,580 megawatt-hours (MWh) [1]. Fiji almost has 80% of its total population access to electricity with 92% of its urban population access to electricity. This work not only helps to fulfil a major part of electricity demand in Fiji but also helps if they are built more at different suitable places as they fulfil the electricity needs of those places as well as nearby areas. It is a true fact that the power generation of Fiji is mainly from the renewable energy sources but Fiji can increase its capability of renewable power generation so that other countries can get more renewable power for the betterment of nature because still the whole world is dependent upon the non-renewable energy sources for its maximum power generation. The paper comprises of the following sections apart from Introduction. Section II focuses on system description. Section III describes methodology that is used in this paper. Section IV shows the simulation model. Section V indicates the optimization results of four chosen areas. Section VI depicts about the conclusion.

## II. SYSTEM DESCRIPTION

In this paper, HOMER Pro® software has been used for designing both on-grid and off-grid hybrid power system. The hybrid system has been analysed for Nakalawaka in Fiji. The software requires some data as input for finding the optimization result of the hybrid model [2]. These data are obtained from the data base of NASA surface meteorology and solar energy for Nakalawaka.

### *A. Load Summary*

Here, the average electric load for Nakalawaka is considered to be 623 kWh/day. Figure 1 show the daily load profile, where it is seen that the peak demand for load is between 17:00 h to 22:00 h in a day. Figure 2 show the seasonal load profile, where it is seen that the peak load is 59.05 kW.

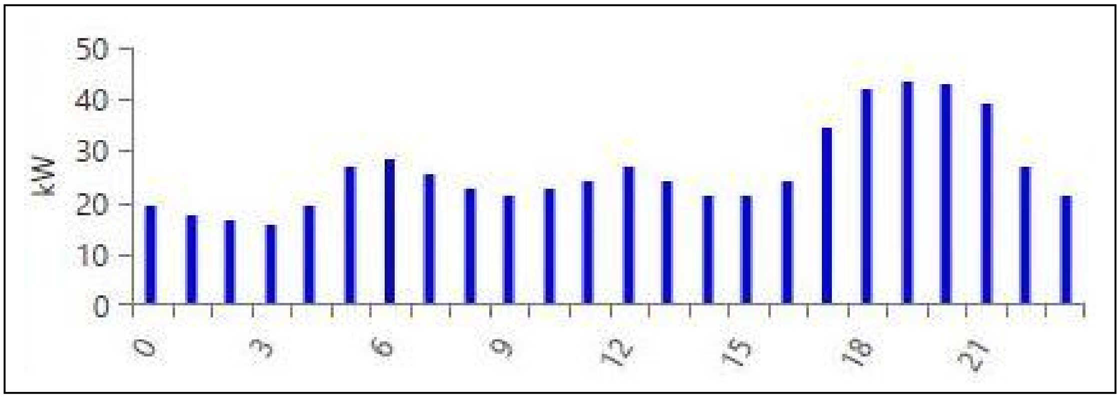


Fig. 1 Daily Load Profile of Nakalawaka

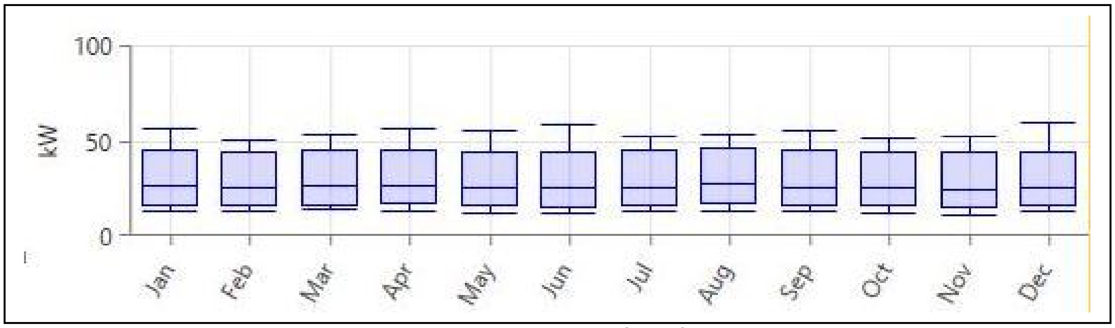


Fig. 2 Seasonal Load Profile of Nakalawaka

*B. Solar Radiation and Wind Speed Details*

The geographical location of Nakalawaka in Fiji is 17°49.9'S (latitude) and 178°32.8'E (longitude). This location is found out by using HOMER Pro® software. All the data regarding solar radiation and wind speed has been downloaded from NASA surface meteorology and solar energy. The annual average solar radiation is 4.79 kWh/m$^2$/day with highest in the month of December. Figure 3 shows the monthly average solar radiation data and clearness index, where it can be seen that the solar radiation ranges from 3.71 kWh/m$^2$/day to 5.67 kWh/m$^2$/day and the clearness index ranges from 0.482 to 0.528. The annual average wind speed is 6.35 m/s with highest in the month of July. Figure 4 shows the monthly average wind speed data, where it can be seen that the wind speed ranges from 5.35 m/s to 7.09 m/s.

*C. Biomass Resource Details*

Here, the annual average biomass is considered to be 8.00 tonnes/day. The carbon content is 2.00 % and the gasification ratio is 0.70. The Lower Heating Value (LHV) of biogas is 5.50 MJ/kg. Figure 5 shows the monthly average biomass data, where all months have equal available biomass i.e. 8.00 tonnes/day.

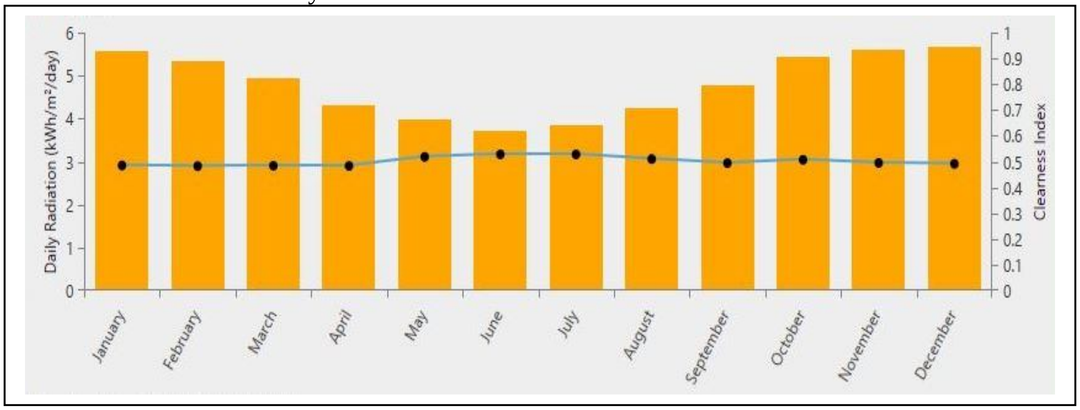


Fig. 3 Monthly Average Solar Radiation Data and Clearness Index of Nakalawaka

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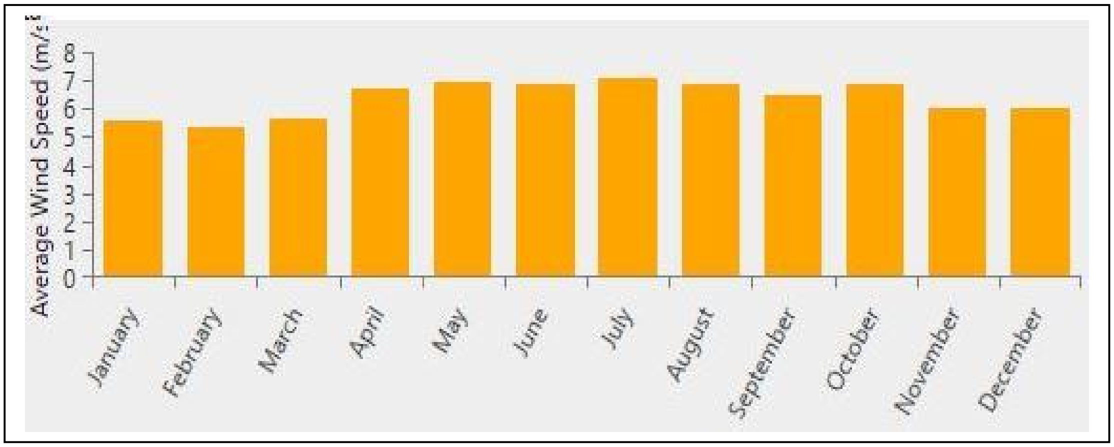


Fig. 4 Monthly Average Wind Speed Data of Nakalawaka

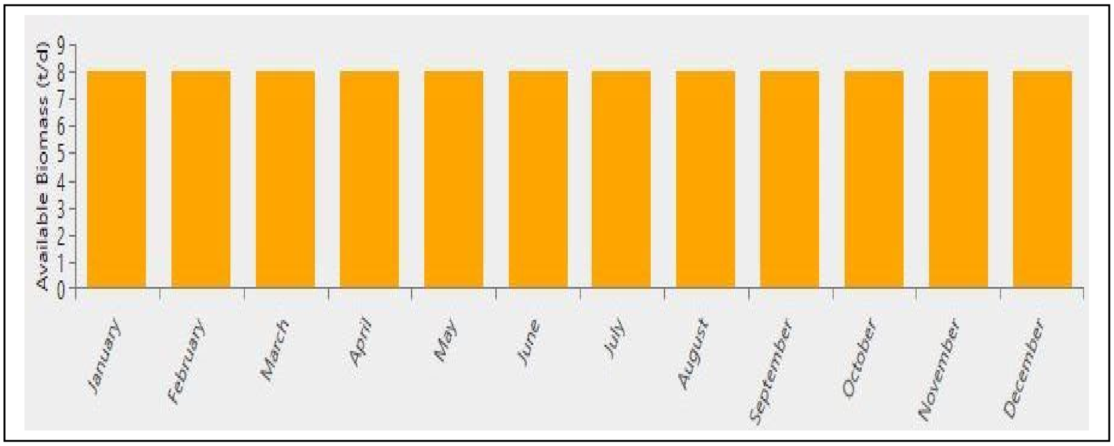


Fig. 5 Monthly Average Biomass Data of Nakalawaka

## III.METHODOLOGY

### A. About HOMER Pro Software

Dr. Peter Lilienthal developed the HOMER software in National Renewable Energy Laboratory (NERL) in United States of America (USA) [3]. In October, 2014 HOMER software was developed into HOMER Pro® version [4]. HOMER Pro® software is used for designing, optimizing and analysing hybrid power system which mainly uses renewable. Designing of models and analysing them for both off-grid and on-grid connected models can be done by using HOMER [5].

### B. Analysis of Cost by using HOMER Pro® Software

1) *Net Present Cost:* The installation cost and operating cost of the system is known as Net Present Cost (NPC). This cost is calculated for the system throughout its lifetime. The formula for NPC is [6]:

$$NPC = TAC / CRF\ (i, Rpr_j).$$

Here, TAC is the Total Annualized Cost in terms of $. CRF is the Capital Recovery Factor. *i* is the rate of interest in terms of %. $Rpr_j$ is the lifetime of project in terms of year.

2) *Total Annualized Cost:* The cost comprising of the addition of the cost of all equipment used in power system which comprises of capital cost, operation cost, maintenance cost, replacement and fuel cost calculated annually is known as Total Annualized Cost (TAC) [6].

3) *Capital Recovery Factor:* The factor which calculates the present value of a series of equal cash flow annually in ratio is known as Capital Recovery Factor (CRF). The formula for CRF is [6]:

$$CRF = \frac{i \times (1+i)^n}{(1+i)^{n-1}}$$

Here, n is the number of years. *i* is the real interest rate calculated annually.

4) *Annual Real Interest Rate:* The Annual Real Interest Rate represents the nominal interest rate as a function. The formula for Annual Real Interest rate is [6]:

$$i = \frac{i' - F}{1 + F}$$

Here *i* is the real interest rate. $i'$ is the nominal interest rate. F is the annual inflation rate.

5) *Cost of Energy:* The average cost in cost/kWh of the system producing electrical energy which is useful in practice is known as Cost of Energy or COE. The formula for COE is [6]:

$$COE = \frac{TAC}{L_{prim,AC} + L_{prim,DC}}$$

Here, $L_{prim,AC}$ is the primary AC load. $L_{prim,DC}$ is the primary DC load.

## IV. SIMULATION MODEL

The hybrid power plant has been designed by using HOMER Pro® software and taking different components from the software. In this paper both on-grid and off-grid solar-wind-biomass hybrid power plant has been designed. The hybrid power system comprises of: PV system, wind turbine, storage battery, load, converter, biomass generator and grid (only in case of on-grid connection). Figure 6 shows the HOMER Pro® model for on-grid hybrid power plant while figure 7 shows the HOMER Pro® model for off-grid hybrid power plant.

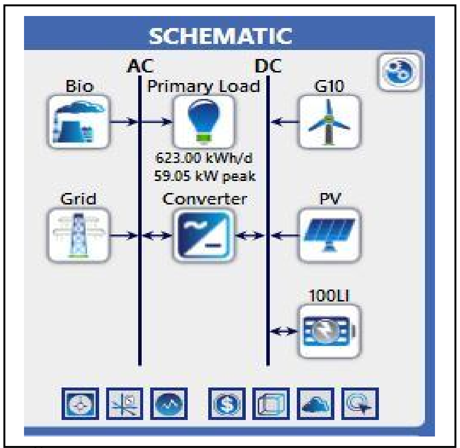


Fig. 6 HOMER Pro® Model for On-grid Hybrid Power Plant of Nakalawaka

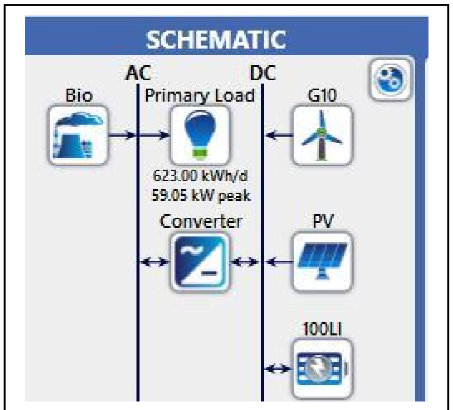


Fig. 7 HOMER Pro® Model for Off-grid Hybrid Power Plant of Nakalawaka

### *A. Photovoltaic (PV) System*
The name of the PV system is Generic flat plate PV manufactured by Generic. The panel is of flat plate type with rated capacity 100 kW. The operating temperature of the panel is 47°C and its efficiency is 13%. Capital cost of the PV panel is 3,000 $/kW along with operation & maintenance (O&M) cost of 10$/year. The lifetime of the panel is 15 years.

### *B. Wind Turbine*
Generic 10 kW wind turbine has been used in this paper which is manufactured by Generic. The rated capacity of each wind turbine is 10 kW and the number of wind turbine used is 10. The capital cost for each wind turbine is $ 50,000 and the O&M cost is 500 $/year. The hub height is 24 m and the lifetime of turbine is 20 years.

### *C. Storage Battery*
In this paper Generic 100 kWh Li-Ion storage battery has been used manufactured by Generic. The nominal capacity of the battery is 100 kWh with nominal voltage of 600 V. The capital cost is $ 70,000 with O&M cost of 1,000 $/year. The efficiency of the battery is 90% and the lifetime is 15 years.

### *D. Converter*
System Converter has been used in this paper manufactured by Generic. The size of the system converter is 1000 kW. The capital cost is 300 $/kW with the O&M cost of 0.0 $/year. The efficiency of the converter is 95% and the lifetime is 15 years.

### *E. Biomass Generator*
The Generic manufactured Biomass Generator has size of 80 kW. The capital cost is 1,000 $/kW with O&M cost of $/op. hr. The minimum load ratio of the biomass generator is 30% and the Lower Heating Value of the generator is 5.5 MJ/kg. The lifetime of the biomass generator is 15,000 hours.

### *F. Grid (in case of On-grid connection)*
In general grid connection used either to give excess power to the grid or to consume power from the grid. When after satisfying the load demand of an area, there is an excess of power, then that excess power can be sale to the grid. On the other hand when there is shortage of power from the Renewable Energy Sources then power can be consumed from the grid.

## V. OPTIMIZATION RESULTS
In this paper we take taken residential load into consideration. The model has been optimized for both on-grid and off-grid condition. So there will be different results for two different conditions.

### *A. On-grid Scenario*
Figure 8 shows the optimization result of the on-grid solar-wind-biomass hybrid power plant. From the optimization result it is seen that the levelized COE is $ 0.805 and NPC is $ 5.16 M. In this condition, the percentage of renewable energy contribution is 81.9%. The cost summary for the optimized hybrid power plant is shown in figure 9, while the net present cost of the hybrid system is shown in figure 10. The annualized cost of the hybrid system is shown in figure 11. The production summary data is shown in Table I, where it can be seen that the total renewable energy generated is 348,604 kWh/yr. The consumption summary data is shown in Table II, where it can be seen that the AC primary load is 227,395 kWh/yr. This shows that hybrid power plant model can easily satisfy the load while generate excess of load. Figure 12 shows the grid purchase (kWh) per month and grid sales (kWh) per month data, where it is seen that quiet a large amount of power is injected into the grid. Figure 13 shows the plot between the solar irradiance in kW/m$^2$ per month and PV power output in kV per month. Figure 14 shows the plot between wind speed in m/s per month and wind turbine power output in kW per month. Figure 15 shows the plot between biomass resource (kg/hr) per month and biomass generator power output (kW) per month

| Architecture | | | | | | | | Cost | | | | System | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PV (kW) | PV-MPPT (kW) | G10 | Bio (kW) | 100LI | Grid (kW) | Converter (kW) | Dispatch | COE ($) | NPC ($) | Operating cost ($/yr) | Initial capital ($) | Ren Frac (%) | Total Fuel (L/yr) |
| 100 | 800 | 10 | 80.0 | 1 | 5,000 | 1,000 | LF | $0.805 | $5.16M | $96,154 | $3.65M | 81.9 | 187 |

Fig. 8 Optimization Result (on-grid) of Nakalawaka

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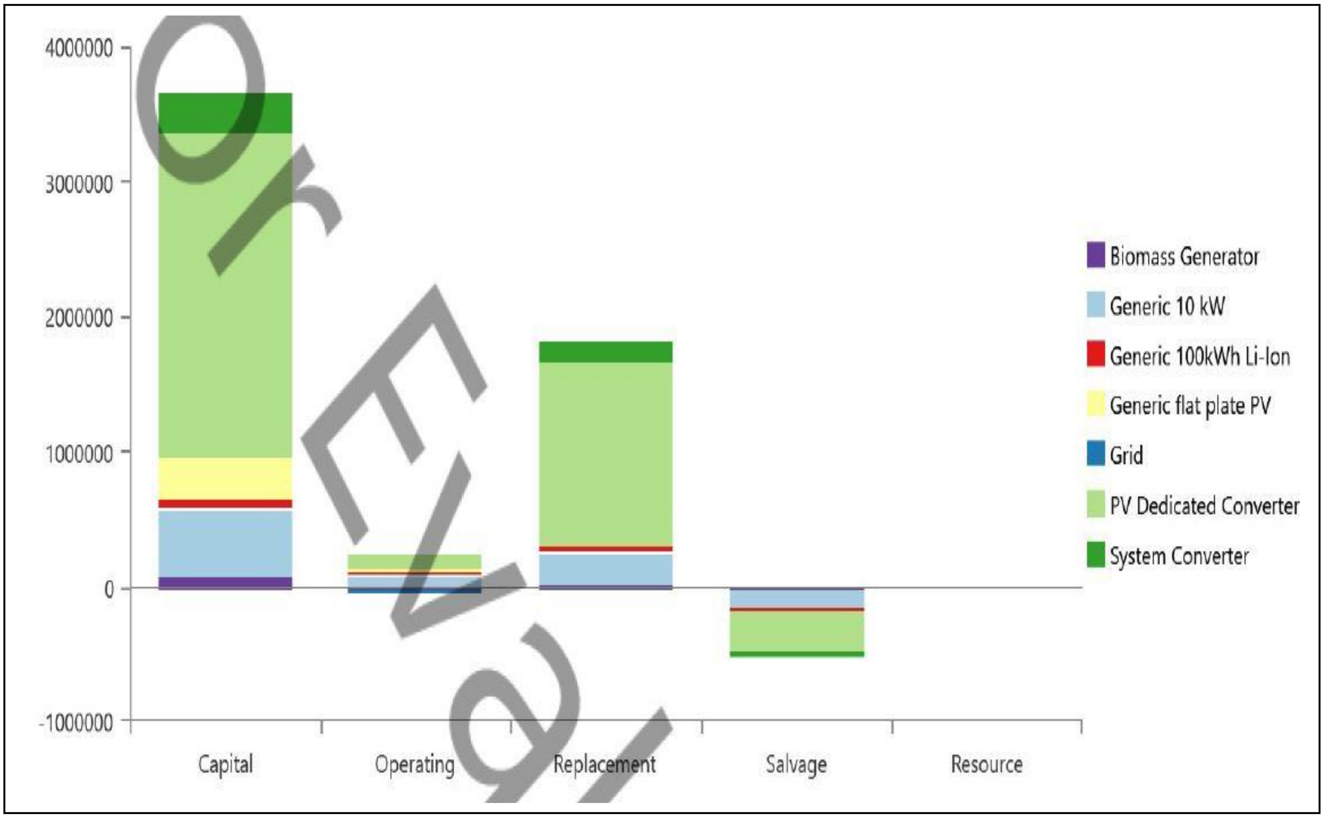


Fig. 9 Cost Summary (on-grid) of Nakalawaka

| Name | Capital | Operating | Replacement | Salvage | Resource | Total |
|---|---|---|---|---|---|---|
| Biomass Generator | $80,000 | $12,707 | $25,687 | -$25,272 | $0.00 | $93,123 |
| Generic 10 kW | $500,000 | $78,762 | $231,663 | -$143,347 | $0.00 | $667,078 |
| Generic 100kWh Li-Ion | $70,000 | $15,752 | $39,311 | -$8,919 | $0.00 | $116,144 |
| Generic flat plate PV | $300,000 | $15,752 | $0.00 | $0.00 | $0.00 | $315,752 |
| Grid | $0.00 | -$25,704 | $0.00 | $0.00 | $0.00 | -$25,704 |
| PV Dedicated Converter | $2.40M | $126,019 | $1.35M | -$305,807 | $0.00 | $3.57M |
| System Converter | $300,000 | $0.00 | $168,475 | -$38,226 | $0.00 | $430,249 |
| System | $3.65M | $223,289 | $1.81M | -$521,571 | $0.00 | $5.16M |

Fig. 10 Net Present Cost (on-grid) of Nakalawaka

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| Name | Capital | Operating | Replacement | Salvage | Resource | Total |
|---|---|---|---|---|---|---|
| Biomass Generator | $5,079 | $806.67 | $1,631 | -$1,604 | $0.00 | $5,912 |
| Generic 10 kW | $31,741 | $5,000 | $14,707 | -$9,100 | $0.00 | $42,348 |
| Generic 100kWh Li-Ion | $4,444 | $1,000 | $2,496 | -$566.22 | $0.00 | $7,373 |
| Generic flat plate PV | $19,045 | $1,000 | $0.00 | $0.00 | $0.00 | $20,045 |
| Grid | $0.00 | -$1,632 | $0.00 | $0.00 | $0.00 | -$1,632 |
| PV Dedicated Converter | $152,358 | $8,000 | $85,562 | -$19,413 | $0.00 | $226,506 |
| System Converter | $19,045 | $0.00 | $10,695 | -$2,427 | $0.00 | $27,313 |
| System | $231,711 | $14,175 | $115,090 | -$33,111 | $0.00 | $327,865 |

Fig. 11 Annualized Cost (on-grid) of Nakalawaka

TABLE I
PRODUCTION SUMMARY (ON-GRID) OF NAKALAWAKA

| Serial Number | Production Summary | | |
|---|---|---|---|
| | Component | Production (kWh/yr) | Percent |
| 1 | Generic flat plate PV | 123,274 | 29.2 |
| 2 | Biomass Generator | 48,400 | 11.5 |
| 3 | Generic 10 kW | 176,930 | 41.9 |
| 4 | Grid Purchases | 73,564 | 17.4 |
| 5 | Total | 422,168 | 100 |

TABLE II
CONSUMPTION SUMMARY (ON-GRID) OF NAKALAWAKA

| Serial Number | Consumption Summary | | |
|---|---|---|---|
| | Component | Consumption (kWh/yr) | Percent |
| 1 | AC Primary Load | 227,395 | 55.8 |
| 2 | DC Primary Load | 0 | 00.0 |
| 3 | Grid Sales | 179,763 | 44.2 |
| 4 | Total | 407,158 | 100 |

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| Month | Energy Purchased (kWh) | Energy Sold (kWh) | Net Energy Purchased (kWh) | Peak Demand (kW) | Energy Charge | Demand Charge |
|---|---|---|---|---|---|---|
| January | 6,882 | 12,715 | -5,833 | 35.4 | $52.47 | $0.00 |
| February | 6,012 | 10,378 | -4,366 | 35.2 | $82.29 | $0.00 |
| March | 7,113 | 12,664 | -5,551 | 35.5 | $78.10 | $0.00 |
| April | 6,019 | 15,976 | -9,957 | 35.5 | -$196.89 | $0.00 |
| May | 5,640 | 17,558 | -11,918 | 35.3 | -$313.90 | $0.00 |
| June | 5,530 | 15,823 | -10,293 | 35.3 | -$238.16 | $0.00 |
| July | 5,556 | 16,811 | -11,255 | 35.2 | -$284.95 | $0.00 |
| August | 6,148 | 16,926 | -10,778 | 35.5 | -$231.53 | $0.00 |
| September | 5,570 | 15,583 | -10,013 | 35.3 | -$222.17 | $0.00 |
| October | 6,213 | 17,706 | -11,493 | 35.4 | -$264.01 | $0.00 |
| November | 6,074 | 13,176 | -7,102 | 35.5 | -$51.38 | $0.00 |
| December | 6,807 | 14,446 | -7,639 | 35.5 | -$41.60 | $0.00 |
| Annual | 73,564 | 179,763 | -106,199 | 35.5 | -$1,632 | $0.00 |

Fig. 12 Grid Purchase (kWh) Per Month and Grid Sales (kWh) Per Month of Nakalawaka (On-grid)

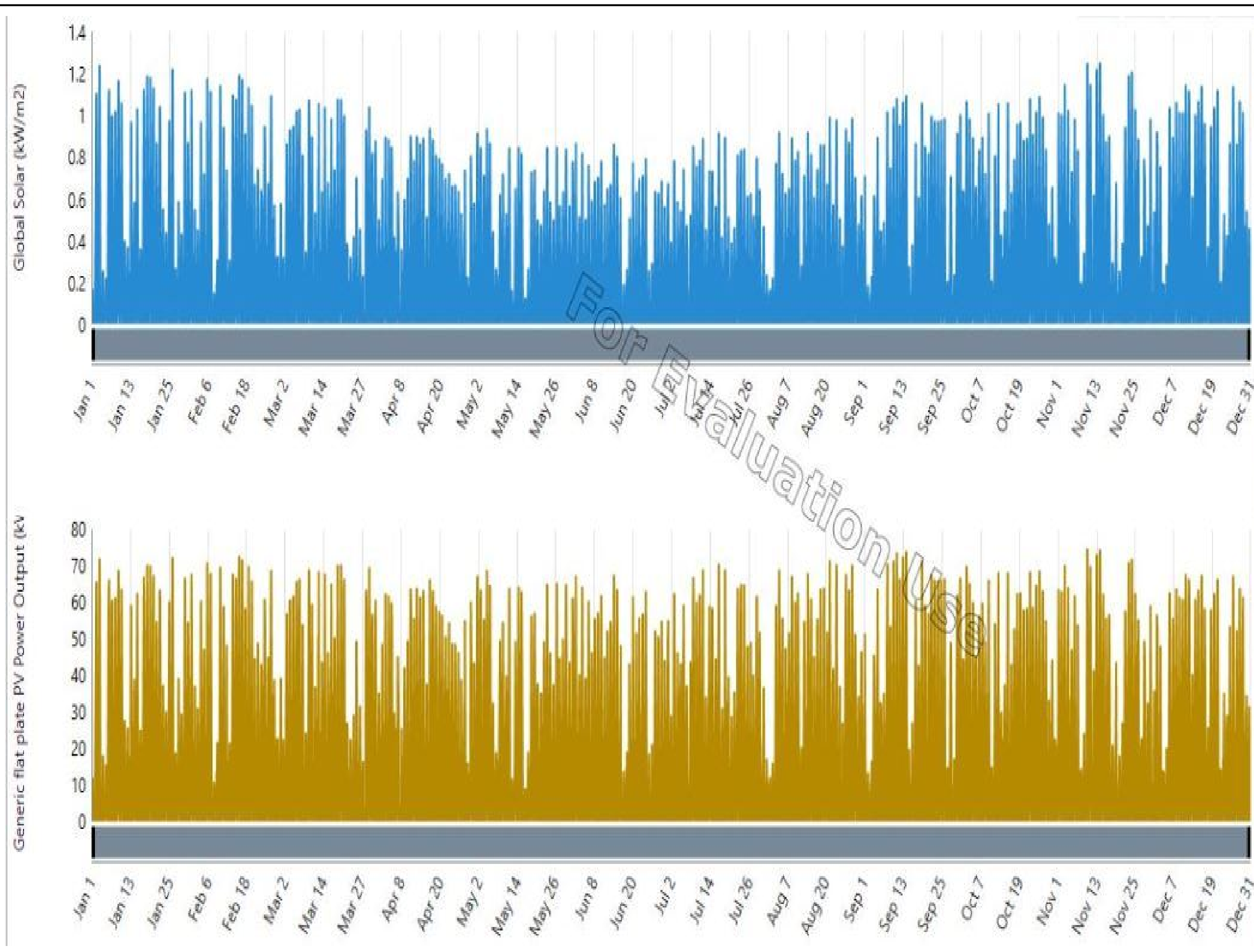


Fig. 13 Global Solar (kW/m$^2$) Per Month and Generic Flat Plate PV Power Output (kW) Per Month of Nakalawaka

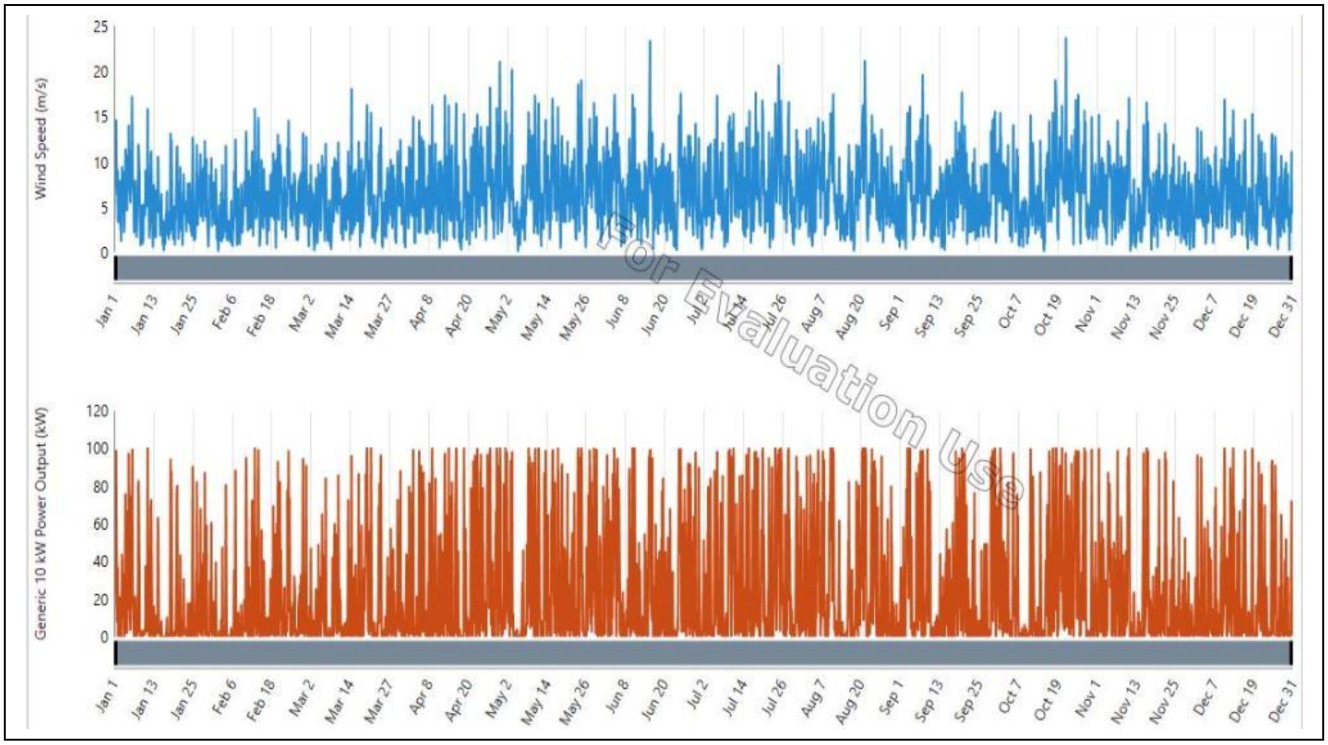


Fig. 14 Wind Speed (m/s) Per Month and Generic 10 kW Power Output (kW) Per Month of Nakalawaka


Fig. 14 Biomass Resource (kg/hr) Per Month and Biomass Generator Power Output (kW) Per Month (on-grid) of Nakalawaka

### *B. Off-grid Scenario*

Figure 15 shows the optimization result of the off-grid solar-wind-biomass hybrid power plant. From the optimization result it is seen that the levelized COE is $ 1.51 and NPC is $ 5.42 M. In this condition, the percentage of renewable energy contribution is 100%. The cost summary for the optimized hybrid power plant is shown in figure 16, while the net present cost of the hybrid system is shown in figure 17. The annualized cost of the hybrid system is shown in figure 18. The production summary data is shown in Table III, where it can be seen that the total renewable energy generated is 381,624 kWh/yr. The consumption summary data is shown in Table IV, where it can be seen that the AC primary load is 227,395 kWh/yr. This shows that hybrid power plant model can easily satisfy the load while generate excess of load. Figure 19 shows the plot between biomass resource (kg/hr) per month and biomass generator power output (kW) per month.

| Architecture | | | | | | | Cost | | | | System | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PV (kW) | PV-MPPT (kW) | G10 | Bio (kW) | 100LI | Converter (kW) | Dispatch | COE ($) | NPC ($) | Operating cost ($/yr) | Initial capital ($) | Ren Frac (%) | Total Fuel (L/yr) |
| 100 | 800 | 10 | 80.0 | 1 | 1,000 | LF | $1.51 | $5.42M | $112,499 | $3.65M | 100 | 474 |

Fig. 15 Optimization Result Snapshot (off-grid) of Nakalawak

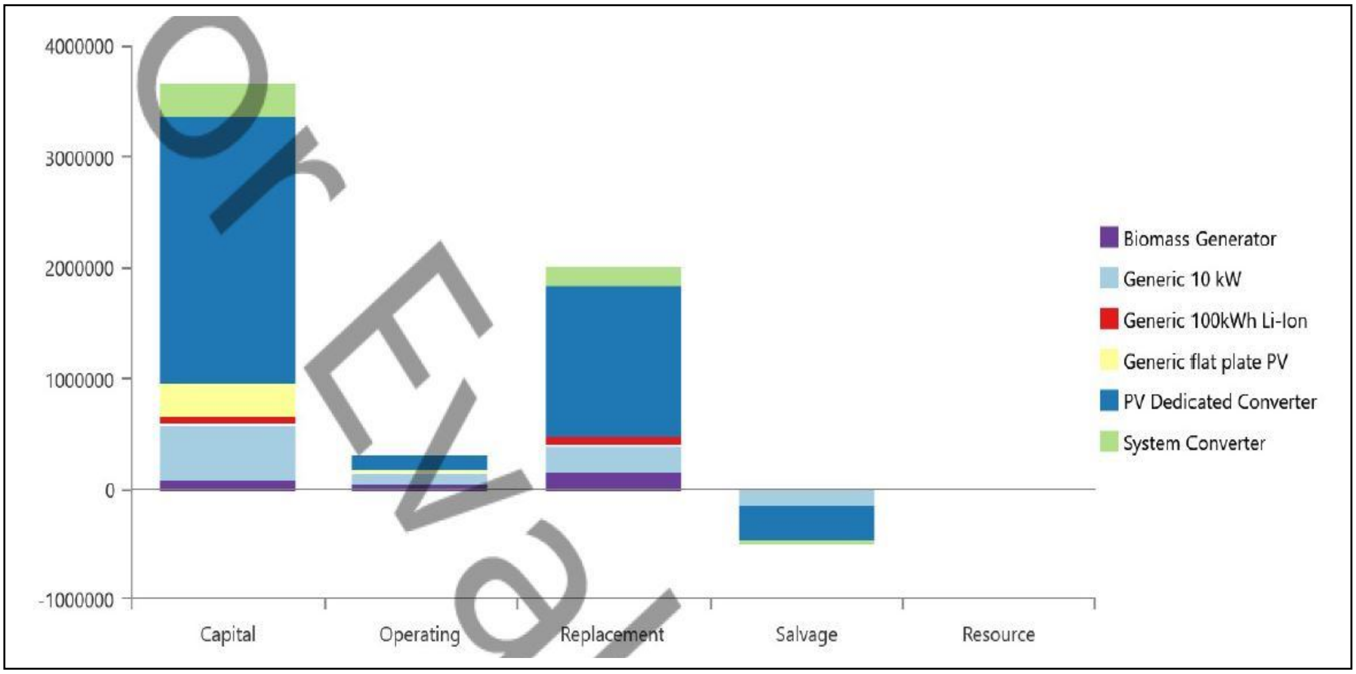


Fig. 16 Cost Summary (off-grid) of Nakalawaka

| Name | Capital | Operating | Replacement | Salvage | Resource | Total |
|---|---|---|---|---|---|---|
| Biomass Generator | $80,000 | $58,179 | $162,748 | -$9,769 | $0.00 | $291,158 |
| Generic 10 kW | $500,000 | $78,762 | $231,663 | -$143,347 | $0.00 | $667,078 |
| Generic 100kWh Li-Ion | $70,000 | $15,752 | $79,059 | -$14,932 | $0.00 | $149,879 |
| Generic flat plate PV | $300,000 | $15,752 | $0.00 | $0.00 | $0.00 | $315,752 |
| PV Dedicated Converter | $2.40M | $126,019 | $1.35M | -$305,807 | $0.00 | $3.57M |
| System Converter | $300,000 | $0.00 | $168,475 | -$38,226 | $0.00 | $430,249 |
| System | $3.65M | $294,465 | $1.99M | -$512,081 | $0.00 | $5.42M |

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| Name | Capital | Operating | Replacement | Salvage | Resource | Total |
|---|---|---|---|---|---|---|
| Biomass Generator | $5,079 | $3,693 | $10,332 | -$620.15 | $0.00 | $18,483 |
| Generic 10 kW | $31,741 | $5,000 | $14,707 | -$9,100 | $0.00 | $42,348 |
| Generic 100kWh Li-Ion | $4,444 | $1,000 | $5,019 | -$947.93 | $0.00 | $9,515 |
| Generic flat plate PV | $19,045 | $1,000 | $0.00 | $0.00 | $0.00 | $20,045 |
| PV Dedicated Converter | $152,358 | $8,000 | $85,562 | -$19,413 | $0.00 | $226,506 |
| System Converter | $19,045 | $0.00 | $10,695 | -$2,427 | $0.00 | $27,313 |
| System | $231,711 | $18,693 | $126,314 | -$32,508 | $0.00 | $344,210 |

Fig. 18 Annualized Cost (off-grid) of Nakalawaka

TABLE IIII
PRODUCTION SUMMARY (OFF-GRID) OF NAKALAWAKA

| Serial Number | Production Summary | | |
|---|---|---|---|
| | Component | Production (kWh/yr) | Percent |
| 1 | Generic flat plate PV | 123,274 | 32.3 |
| 2 | Biomass Generator | 81,420 | 21.3 |
| 3 | Generic 10 kW | 176,930 | 46.4 |
| 4 | Grid Purchases | 0 | 00.0 |
| 5 | Total | 381,624 | 100 |

TABLE IV
CONSUMPTION SUMMARY (OFF-GRID) OF NAKALAWAKA

| Serial Number | Consumption Summary | | |
|---|---|---|---|
| | Component | Consumption (kWh/yr) | Percent |
| 1 | AC Primary Load | 227,395 | 100 |
| 2 | DC Primary Load | 0 | 0 |
| 3 | Grid Sales | 0 | 0 |
| 4 | Total | 227,395 | 100 |

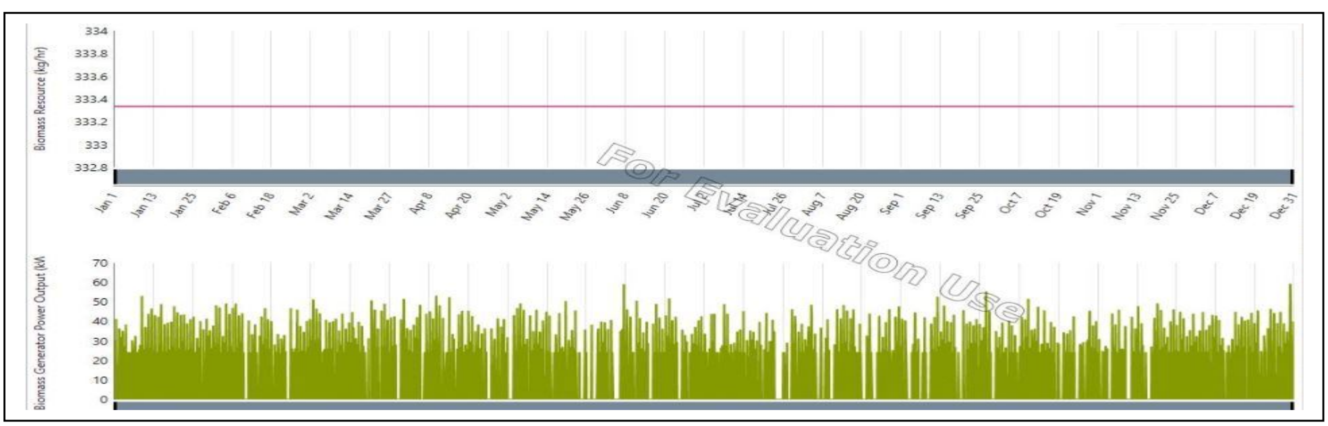


Fig. 19 Biomass Resource (kg/hr) Per Month and Biomass Generator Power Output (kW) Per Month (off-grid) of Nakalawaka

## VI. CONCLUSION

The overall conclusion of this work is that the solar-wind-biomass hybrid power plant is more profitable in on-grid than off-grid since it sells a large amount of power in grid every year and purchase a comparable low amount of power from every year. Moreover, the levelized COE in case of on-grid mode is only $0.805 and the NPC is $ 5.16M while in case of off-grid mode the levelized COE is $ 1.51 and the NPC is $ 5.42M. So in terms of cost analysis we can see that on-grid mode is highly practicable than off-grid mode since both the COE and NPC is low in on-grid as compare to off-grid mode. Both the on-grid and off-grid analysis helps us to understand that the scope of renewable power generation in Fiji is very good as well as it can generate a large amount of extra power which can be used for selling. If such kind of hybrid system built at more suitable places by making contracts agreements in between different countries of the world then such hybrid system at a very large scale solve the problem of pollution from thermal power plants to a very large extent. Also it connects the whole world in terms of electricity just like internet.

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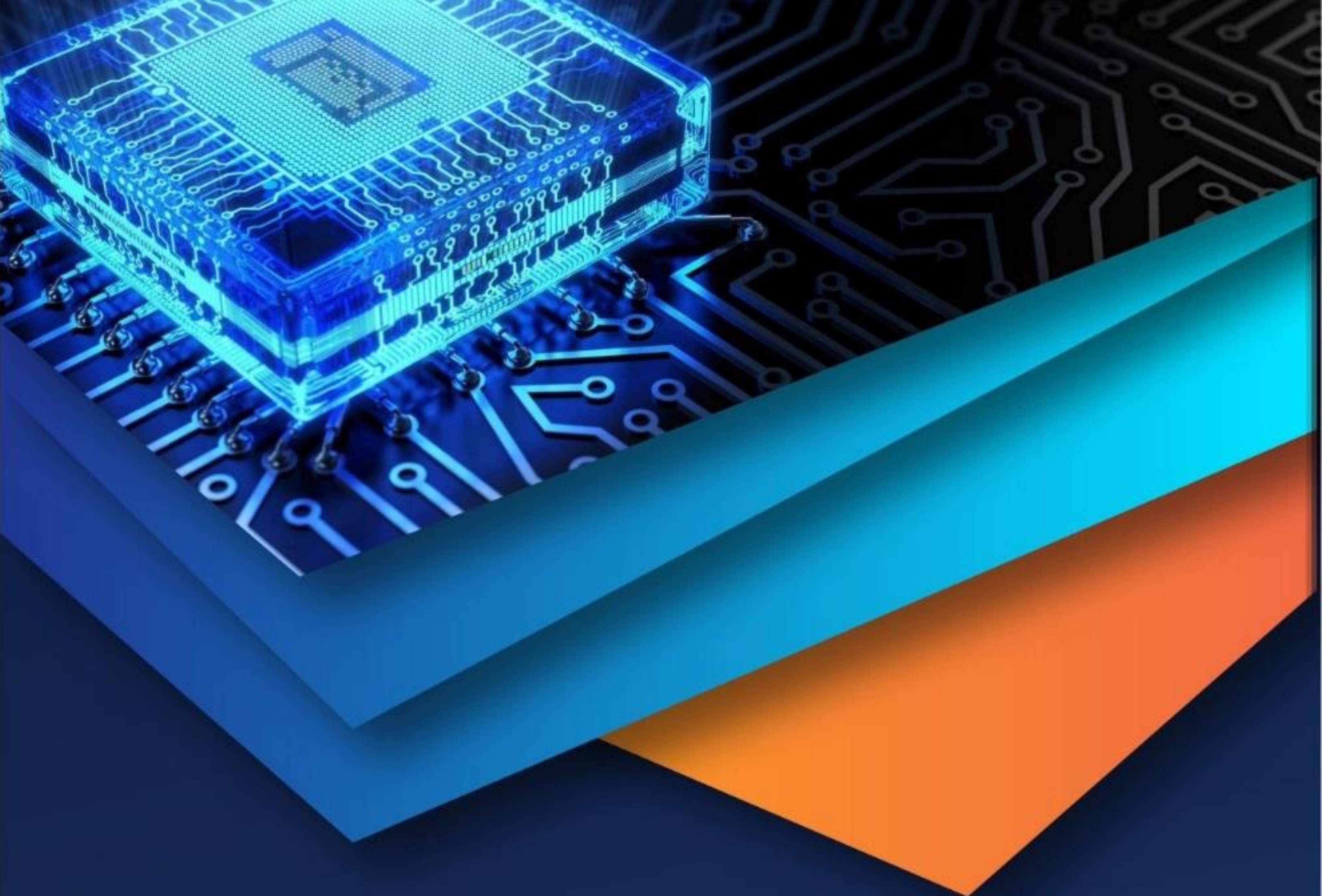


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