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Cost-Benefit Analysis of Solar Power Implementation in off-Grid Regions

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Abstract- The purpose of this study is to investigate the economic viability and social impact of transitioning to renewable energy sources. This will be accomplished by conducting a cost-benefit analysis of the building of solar power systems in places that are not connected to the mainstream power grid. More specifically, the consequences of making the conversion to solar power will be the primary focus of the study. The research takes into account both the initial investment costs (panels, batteries, inverters, installation) and the ongoing expenses (maintenance, replacement) that are linked with the consumption of solar electricity. These costs are taken into consideration. The benefits that have been examined include increased access to energy, decreased reliance on fossil fuels, the creation of jobs, improvements in education and healthcare, and enhanced chances for economic development. These benefits have been analyzed. Additionally, an analysis of the advantages has been carried out. The primary focus of this investigation is on the unique difficulties and components that are associated with areas that are not connected to the centralized power system. The remoteness of the place, the community's involvement, and the system's scalability are some of the characteristics that contribute to what makes this situation unique. The goal of this cost-benefit analysis (CBA) is to give decision-makers critical insights into the viability and overall worth of solar power projects in locations that are not provided with grid power. This is accomplished by assessing and contrasting the costs and advantages of the project. In the end, this will help the development of sustainable behaviors as well as the production of policy decisions that are informed by relevant information.

Keywords- Cost-benefit analysis, Solar power, Off-grid, Renewable energy, Rural Electrification

I. INTRODUCTION

Reliable and affordable electricity is necessary for the development of modern societies, promoting economic growth, social well-being, and lifestyle. However, a large part of the world's population needs access to this basic resource, especially in isolated off-grid areas [1]. Diesel generators are typically used in these communities for off-grid power, which is generally unsustainable and expensive while impacting the environment by creating carbon emissions and air and noise pollution [2]. Solar energy, in particular, was poised to be a part of the solution to this dilemma and even further sustainable development goals.

Solar power is one of the most promising and practically feasible decentralized indigenous approaches that promises to provide clean, renewable, and cheaper off-grid electricity from abundant solar energy resources [3]. The decreasing expenses associated with solar photovoltaic technology, along with improvements in battery storage and system design, have rendered solar power generation a viable option for these remote regions [4]. Studies have shown the potential of off-grid solar PV systems to provide electricity in remote areas, illustrated by a case study from India [4].

Figure 1: Negative impacts of fossil power and Positive renewable energy respectively [20].

This analysis performs a complete cost-benefit evaluation of the integration of solar power systems in remote areas. CBA, in essence, serves as a tool for identifying the overall costs and benefits of conducting or not carrying out (producing) a project, namely evaluable factors to depict whether building any project source is economically reasonable [5] [6]. It includes costs to install solar power generation and operation as well as benefits such as expanded electricity access, decreased dependence on fossil fuels, the installation of new jobs at rates greater than current coal mining jobs (in most cities), opportunities for improved education or healthcare services locally availability in schools/public libraries near future projects linked directly back into regional economic growth.

This paper aims to discuss particular characteristics of off-grid areas, which include dispersal or remoteness challenges, community-based approach, and solar power solutions scalability. This CBA quantifies and compares the costs or benefits of any given option for decision-making aimed at understanding the financial viability, as well as the overall value proposition regarding solar power projects in off-grid communities. In the end, this research is also in favor of making informed policy decisions and thereby contributes to universal energy access in support of sustainable development goals.

II. LITERATURE REVIEW

There is a body of literature addressing off-grid electrification and the position that solar power holds in supplying energy access. Many different studies have explored the technical, economic, and social implications of off-grid solar systems in sustainable development [1][7]. In the literature, several issues have been discussed on off-grid solar PV systems, especially the Sustainability and implications for rural electrification in developing countries [1], as well as barriers of solutions to increase penetration rates of solar energy into the electricity mix [8]. Also, research has been conducted on hybrid systems (PV hydro) for remote area electrification [9].

Solar energy projects being renewable are studied with the help of cost-benefit analysis. In previous studies, CBA has also been applied to evaluate the economic returns and other factors on solar power investments, such as initial costs of investment operational cost along with units produced [10][11]. For instance, (Akter et al.) Quantitative analysis [10] undertook an economic evaluation of a residential building coupled with solar photovoltaic and battery energy storage systems in Australia. More recent studies have also used CBA in energy efficiency projects targeting a public building, demonstrating the importance of this method in assessing the cost and benefits of sustainability attributes [12].

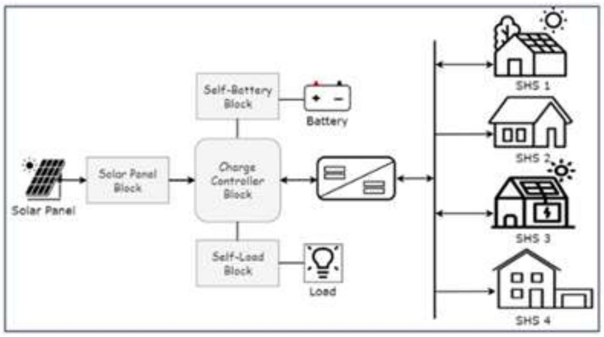

Figure 2: Design of control system architecture with individual SHSs [21]

Policies and regulations are essential facilitators for the uptake and development of off-grid solar systems. The global adoption of renewable energy has been promoted by many governmental policies and incentives, including feed-in tariffs (FITs), tax credits, and net metering programs [13]. Assessing these policies and regulations provides insights into the influence of various policy instruments on the expanding solar power sector [14]. Moreover, research has investigated the obstacles to the implementation of photovoltaic systems, pinpointing elements such as substantial initial expenses, inadequate access to financing, and insufficient customer knowledge [15].

A multitude of critical factors influence the acceptance and efficacy of solar electricity in off-grid areas. This encompasses the accessible local solar resources, community energy consumption trends, technical feasibility of implementing solar power systems, and the economic expenses associated with adoption[3]. Social considerations, including community-level support and acceptability, are essential for effectively implementing solar power systems[16]. These variables are essential to consider while devising strategies for mainstreaming solar power utilization in off-grid regions. Research has examined a potential socio-political adaptation regime for solar energy in the Global South, concentrating on the accompanying risks and opportunities of its adoption

[2]. Furthermore, the literature has also examined the use of innovative business models and service delivery to promote access to solar power [17]. This study's approach is preliminary and employs a typical cost-benefit analysis to assess some of the economic possibilities for solar power systems in off-grid, primarily rural regions. This approach relies on counting the deployments of identification over some period as going through a cost-and-benefit process.

III. METHODOLOGY

A social point of view is taken, considering the sum of complete charges and benefits in flip to society. The established CBA guidelines [5] [6], informed the analysis making it a stringent and transparent appraisal. For cost data on individual components where they are not available, the values were estimated based on reliable sources of reserves and best industry practices.

This includes outlining the different cost components, such as capital and operational expenditures. The cost analysis of this study may benefit from the works on cost frameworks for PV mini-grids as reported in (A. Bruce) [18].

Figure 4: Dimensions of CBA methodologies

Cost and Benefit Identification

Costs: Other than the upfront capital costs associated with purchasing and installing solar panels, batteries, inverters, etc. These costs have a lot to do with the system, so one is maintenance, and other components will be replaced over time.

Advantages: Increased electricity access, reduced reliance on fossil fuels (e.g. diesel generators), job opportunities within established renewable energy sector improve in sustainable energy employment and service delivery continues with more reliable power supplies likely supporting socio-economic development perspective.

Data Sources and Quantification: Cost data comes from various sources such as solar system and component manufacturers, suppliers as well installers. Methods to evaluate benefits: — Market prices, avoided costs, and contingent valuation techniques.

Discount Rate and Time Horizon: The discount rate is a percentage that reflects the time it would take to be paid returns of profit over an extended period. The analysis had a profitability time horizon of 20-25 years, representing the average lifecycle for solar power systems.

Figure 5: The Role of Discount Rate in Evaluating Future Costs and Benefits [22]

Sensitivity Analysis: A model is developed and a sensitivity analysis is conducted to understand the impact of changes in key factors (e.g. solar radiation, energy demand growth, or discount rate) on CBA results; These analyses help you recognize what matters most to your project profitability and support decision-making under uncertainty

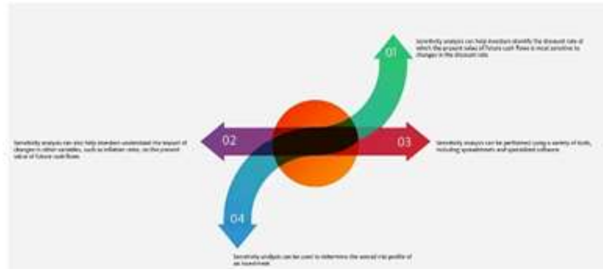

Figure 6: Sensitivity analysis and its role in the discount rate [22].

IV. RESULT

This section deals with the justification of how much it costs and benefits metrically to have a solar power system for off-grid locations. The results (illustrating the methodology described in Section III) have been desiccated for various solar PV system installations and scenarios.

Equation of PV in the Array

Output from PV arrays mostly depends on array size, derating factor, solar radiation, and temperature. To compute that output, HOMER uses this equation below [23].

$$P_{PV} = C_{PV} f_{PV} (I_T/I_{T,STC})[1 + \beta_P(t_C - t_{C,STC})] \quad (1)$$

here, C_{PV} is PV array capability (kW), f_{PV} is the derating factor of PV panel [%], I_T is in the current time step, solar energy strikes the array in kW per m^2, $I_{T,STC}$ is in conventional test conditions, incident radiation kW/m^2, β_P is the heat coefficient of energy in %/^{o} C, t_C is current time step's cell temperature in degree Celsius and $t_{C,STC}$ is temperature of cells under typical circumstances for testing [25 ℃].

HOMER's cost analysis procedure

The sum of the C_{PV} and converter costs C_{CONV} is the system cost.

$$C_{System} = C_{PV} + C_{CONV} \quad (2)$$

Net present cost: Total installation and operation costs over its lifetime, are determined as [24]:

$$NPC = A_C/R_F(i,P_L) \quad (3)$$

where, A_C , R_F ,i , and P_L represent total annualized cost, capital recovery factor, the interest rate in percentage, and system lifetime in years, respectively.

Annualized Cost

The sum of all equipment's annualized costs, including capital, operation, and maintenance, including replacement and gasoline costs [24].

Figure 7: Map showing the location of the DUBLAR CHAR

$$C_{Annual} = (CCR_F + CO) \quad (4)$$

Capital recovery factor: It is a ratio that calculates the present value of equal annual cash flows [24].

$$R_F = (i \times (1 + i)^n/((1 + i)^{n-1}) \quad (5)$$

where n denotes the length of time and i the denotes yearly real interest rate.

Cost of Energy: It is the average cost per kilowatt-hour of usable electricity produced by system [24]:

$$COE = A_C /(D_{Pr(AC)} + D_{Pr(DC)}) \quad (6)$$

here, $D_{Pr,(AC)}$ denotes primary load of AC and $D_{Pr,(DC)}$ is DC primary load.

Study Site and Rooftop Illustration

DUBLAR CHAR is located at 21.81^0 North latitude and 89.56^0 East longitude, as illustrated in Figure 7, which is an area that is disconnected from the utility grid to meet its energy requirements. The geographical location of the location is DUBLAR CHAR, Bagerhat, Khulna, Bangladesh.

Electrical Load Profile of DUBLAR CHAR

Around 3,000.00 people are living in DUBLAR CHAR has around 300-400 living places including, offices, houses, markets, etc. according to the survey. The load demand was investigated across the site and is presented in Table 1. It has a load of 208.25 kW and a total of 5740 pieces of equipment. The maximum load demand of DUBLAR CHAR in summer is about 185 kW/day and in winter it is about 124 kW/day.

Table 1: Estimated electrical load in DUBLAR CHAR.

Appliance	Quantity	Rated power (Watt)	Total power (Kilo Watt)
Light	1500	18	27
Fan	1000	100	100
Refrigerator	50	270	13.5
Drinks freezer	20	330	6.6
Desktop	30	220	6.6
Surveillance camera	50	6	0.3
Television	70	75	5.25
Charger	3000	15	45
Halogen light	20	200	4
Total	5740	1234	208.25

Technical and Economic Input Parameters

Photovoltaic Modules

The PV array's output is proportional to the amount of solar energy it receives. Like, a panel generates 80 percent of its rated output if solar radiation is 0.80 kilowatts per square meter [25]. In a manual calculation using our rooftop area and PV module dimension values, it was estimated that our study site is capable of arranging a 145–175 kW capacitive PV array on the rooftops. Therefore, this study includes 0-kW, 100-kW, 200-kW, and 250-kilowatt, of proposed solar PV arrays. This analysis considers the temperature effect and applies a derating factor of 88% to photovoltaic modules with an efficiency of 19.88% and a lifespan of 25 years. The capital and substitution costs for solar photovoltaic systems are estimated at USD 980 per kilowatt, while the operation and maintenance expenses amount to USD 0.65 annually.

Power Converter

The simulation model incorporates a power converter exhibiting 98.0% efficiency and a lifespan of 15 years, with capital and replacement costs of $80 per kilowatt and operating and maintenance (O&M) expenses of $1.80 annually. The converter operates in inverter mode to supply the grid with alternating current.

Grid

A nominal discount rate of 8% and a 6% inflation rate were applied in this simulation with both load-following and cycle-charging dispatch strategies [26]. The capacity shortage penalty is not taken into account throughout the planned project's 20-year lifespan. The maximum renewable portion was also determined to be 100%. Based on total NPC, COE, and renewable energy penetration (%). The NPC is the resultant of the current value of all connected expenditures minus the actual value of all earnings during the project's lifetime. This covers initial investment, restoration, operational, and maintenance costs, as well as penalties on emissions.

Optimized outcome

The assessed simulations, optimizations, and sensitivities according to specified supplies and limitations to select the most likely system. The system with a diesel generator only, requires a 300-kW diesel generator with a price of diesel $0.88 per liter, with an annual diesel usage for diesel generator systems of 3,575,520.00 liters. It gives the worst performance, with COE of 50.4 dollars/kilowatt-hour, a net present cost of 441,714.24 dollars which is much greater than the PV array system.

Comparison of System Configurations and Scenarios

The similarities of solar power systems are evaluated in relation to their economic performance in the field, assuming identical high-quality model parameters, including minor variations in sizing and payment plans. This comparison provides insights from estimated economic variables to determine the most cost-effective and efficient system design for off-grid scenarios.

Social and Environmental System Level Impacts

This part further analyzes social benefits, together with different environmental points related to the adoption of solar energy in off-grid communities. Socially: Greater access to education and health services, increased employment opportunities, and community development. During operation, the environmental benefits of NOMADs are lower compared to traditional diesel generators because they reduce greenhouse gas emissions while enhancing air quality and reducing noise pollution.

V. DISCUSSION

The cost-benefit analysis concludes that there is great potential for implementing solar power systems in off-grid regions. The announcement of those results and their relevance to the formulation of policies or introduction of projects is an important aspect that must be considered.

Analysis Constraints and Prospective Investigations Cost-Benefit Analysis (CBA) is an effective technique for assessing the economic viability of solar energy. Nonetheless, it possesses certain restrictions. Cost-Benefit Analysis (CBA) primarily addresses measurable costs and benefits, neglecting significant non-quantitative issues such as social equality, environmental sustainability, and community acceptance. In addition, the quality of CBA results is highly sensitive to data inputs and assumptions on future conditions. One possible direction for future research is to investigate how non-market values, such as health gains and environmental benefits, could more systematically be incorporated into the framework of CBA. Moreover, to make the cost and benefit estimation more accurate, we need to research how well solar power systems work in an off-grid context over time.

VI. CONCLUSION

The results of the study indicate that solar energy has a high capacity for off-grid electrification and can serve as an affordable solution to meet basic household demand in isolated territories with minimal emissions into the atmosphere. According to the results of their cost-benefit analysis, biodiesel plants produce a negative net present value (hence are economically unviable and not financially attractive). However, solar power projects generate positive values that indicate that they can deliver good returns to investors. The positive CBA ratios also emphasize the economic potential of solar power over conventional sources, specifically in regions with restricted grid access.

These results have clear policy implications for scaling up solar power in off-grid communities. These tools are streamlined permitting processes, targeted financial incentives, and technical assistance programs to make solar project applications easier for customer-host developers. In addition, local ownership and involvement of communities in solar projects can also create demand for long-term Sustainability, thereby achieving greater social disadvantages that derive from the system or are affected by it. Also, brand-new jobs can be developed through investment in workforce development and training programs, which the renewable energy industry will employ.

Solar power is one of the simplest solutions to sustainable development goals. Solar energy can help save lives by enabling health delivery, helping ensure a safer and healthier life, allowing for short-term access to education, and assisting in attracting teachers working in the area. It also helps drive the economic development of off-grid communities. On a larger scale, the decreased necessity of fossil fuels due to solar power usage is effective against climate change and helps clean our air

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