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Evaluation of Off-grid Photovoltaic Projects for Schools and Health Posts in Angola

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ABSTRACT

Most regions in Sub-Saharan Africa still cannot sufficiently meet electricity needs and, although access to electricity has been increasing, electricity access remains a fundamental problem for the region. Several countries have endogenous energy resources, including important oil and gas reserves, and high renewable energy resources potential. Despite these favourable conditions, these regions face a critical challenge in providing access to electricity, particularly in socioeconomically vulnerable regions that still rely on diesel generators to meet their basic electricity needs. This study focuses on off-grid photovoltaics projects in Sub-Saharan Africa, addressing the cases of electricity supply to schools and health posts in two localities in the Centre and South regions of Angola. The analysis includes a first assessment of the avoided CO_2 emissions and the traditional discounted cash flow method, complemented by a Monte Carlo Simulation to identify key uncertainties. The results show that the economic viability of the projects is significantly compromised by low subsidised diesel prices. Nevertheless, it is crucial to recognize the importance of these projects for the sustainable development including health improvements resulting from the reduced use of highly polluting diesel, increased electricity security of supply and advances on the literacy of deprived populations.

KEYWORDS

Energy planning, Project evaluation, Photovoltaic, Sub-Saharan Africa, Sustainable development, Education, Health.

INTRODUCTION

Numerous studies have established a strong correlation between per capita energy consumption and well-being indicators (e.g. [1]). In developing countries, it has been associated with higher literacy rates [2] and increased employment opportunities [3], for instance. Consequently, there is a growing body of literature advocating for the integration of social considerations into energy and electricity planning (e.g. [4]). Dagnachew *et al.* [5] highlighted the significance of considering productive uses of electricity in power planning

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approaches. This underscores the importance of understanding not only how electricity is generated but also how and by whom it will be consumed, especially in developing countries with varying levels of electricity access. Bissiri *et al.* [6] echoed this statement in their review of power systems planning approaches in West Africa. Likewise, Justo *et al.* [7] reviewed power planning approaches in the Southern African Development Community member states, highlighting shortcomings in dealing with renewables' intermittency and the high suppressed demand in the region.

Developing countries in Africa mainly rely on fossil fuels for electricity generation and to some extent on hydropower. Other technologies such as photovoltaic (PV) are still in the early stage of implementation and their wide dissemination presents important challenges. However, it is recognized that decentralized production can play a key role in the development of poor regions bringing considerable benefits to the population living in villages with no access to the central grid and relying on local public services. Access to electricity is a central dimension of reducing poverty and supporting economic growth [8].

Most African regions suffer from the main challenges facing developing countries and require critical attention including poverty, uneven distribution of national income, and several social problems [9]. Ebhota [10] called attention to the low development stage of the power sector in the Sub-Saharan Africa that cannot sufficiently meet electricity needs, as required by the growing population and economic growth. Although access to electricity has been increasing, it only reached less than 51% in Sub-Saharan Africa in 2021 and this value is even lower for the rural population, reaching only 30.4% [11].

Currently, nearly 600 million people in Africa lack access to electricity and approximately one billion Africans do not have access to clean cooking energy [12]. In this context, renewable energy (RE) emerges as a promising avenue for Africa to bridge its electricity gap [13]. Unfortunately, RE investment on the continent has remained relatively low in recent decades, primarily due to funding and financing challenges [14]. Despite Africa's substantial share of the global population, it attracts only 3% of global energy investment, accounts for just 6% of global energy consumption, and represents a mere 3% of global electricity demand [15]. As electricity access has been associated with positive feedbacks on social development in Sub-Saharan Africa, a region that has historically struggled with low-electricity access [16], energy investment will not only make progress towards Sustainable Development Goal (SDG) 7 but also improve living conditions as a whole. This is particularly true in impoverished rural households, as highlighted by Mboumboue *et al.* [17] for Cameroon. Understanding the intricate connections among social, economic, technical, and environmental facets underscores the central role of clean electricity access in Africa's energy transition. While power planning approaches have evolved considerably, incorporating models for both on-grid and off-grid systems and enhancing RE grid integration, they remain predominantly focused on techno-economic aspects [13]. This is a critical concern as Africa's electricity challenges are not solely related to funding and technology but are also influenced by socio-political factors. Newell *et al.* [18] emphasized that electrification extends beyond business models and pricing, involving the construction of new social, cultural, and political systems.

The solar power resource is abundant in Africa and offers opportunities for the development of PV solutions to support distributed electricity supply in rural regions. According to [19] SWOT analysis, the main strengths and opportunities are related to the increasing concerns about climate change and the decline of PV costs. However, the authors also called attention to the weaknesses, such as the high capital expenditure (CAPEX) required and the limited knowledge of the technology in the African countries along with the threats related to fossil fuel dominance and the less favourable policy environment. PV-powered stand-alone systems are becoming the most popular way of producing electricity far from the grid and is expected that off-grid rural electrification in Sub-Saharan Africa will be driven by this technology [20]. The technology is particularly relevant due to the high solar irradiance in the region, the increasing affordability and the modularity of the technology. Moreover, batteries may have an important role to play although their uptake is currently constrained by the costs of equipment [21].

Babayomi *et al.* [22] underlined the importance of mini-grids powered by solar PV not only for rural communities but also for the underserved peri-urban and urban areas [22]. While the authors highlighted several barriers that still limit PV development including weak regulatory and policy frameworks, and financial requirements, they also called attention to the energy justice concept and the importance of the potential gains from the consumers' empowerment and improvement of the economic activities and living conditions.

The case of high CAPEX costs for PV systems is also debated for different case studies in Sub-Saharan Africa, as is the case of Zambia, showing the need to improve policies supporting these systems and addressing the effect of diesel prices uncertainty on the generation investment decision making [23]. Based on this case, that authors concluded on the importance of the solar PV solutions for Sub-Saharan Africa. Realizing the Sustainable Development Goal (SDG) number 7 requires reaching reliable access to clean electricity, which is also a fundamental driver to reduce poverty and support economic growth. The study of [24] confirms this positive interaction between electricity and other SDG, therefore electricity access not only provides energy services but also benefits more people by ensuring, for example, better health condition and bringing better education.

While demonstrating the potential for PV, these studies also showed the uncertainty surrounding the decision-making process, particularly the importance of CAPEX and diesel prices to justify the investment. Moreover, it is clear that these is the need to move beyond a pure economic assessment and analyse the projects from a SDG perspective, recognizing electricity access as a key factor to promote social and economic development. This demonstrates that the issue of PV use in developing countries, along with its economic and social importance, is still far from being fully considered in the literature, leading to the proposal of the following research hypothesis:

The economic viability of PV microgeneration systems is significantly influenced by the cost and governmental conditions specific to each country and region, and can lead to substantial sustainability gains beyond SDG 7 - Affordable and Clean Energy.

This paper aims then to test the hypothesis by revisiting the case PV in Sub-Saharan Africa but now addressing the specific cases of health units and schools to respond to the following research questions:

- What factors may affect the economic viability of PV microgeneration with and without energy storage in Sub-Saharan Africa?
- How does PV microgeneration may contribute to sustainable development in Sub-Saharan Africa?

This research is based on a multiple case study approach in different locations of a Sub-Saharan African country. This included the economic analysis of distributed PV microgeneration in the Centre-South regions of Angola, close to Ombadja-Cunene and Lubango-Huíla. The study aims to assess the potential for using PV in two locations to supply electricity to a health post and a school with different consumption patterns. These two cases are directly related to some of the main sustainable development challenges of the country: health and education for all.

The selection of the case is justified by for two main reasons. Firstly, the case of energy planning in Angola remains largely unexplored in the literature, with a few exceptions. One such exception is by [25], who addressed the case of the province of Namibe, Angola, concluding on the importance of combining different renewables and natural gas in the electricity system. The importance of distributed generation was highlighted by [26], who emphasized the concept's significance, considering the needs of different regions of the country. More recently [27] explored the use of wind and solar power to supply a house in the province of Moxico, Angola, and concluded on the higher cost-effectiveness of solar power. However, important aspects related to the economic viability of the PV system, its environmental benefits, and its contributions to the education and health sustainable development challenges of the country still require extensive research. Secondly, Angola represents an important case that mirrors the main challenges of the Sub-Saharan Africa in what concerns energy access, health and education allowing then to test the research hypothesis.

One of the main criticisms of case studies is that it is impossible to generalise the results obtained, however the case study can be central to scientific development [28]. The proposed cases should allow to improve understating on the main aspects jeopardizing the economic viability of PV systems and on how their use can contribute to other SDG beyond SDG 7- Affordable and clean energy, including SDG 3- Good health and well-being and SDG 4- Education Quality. This provides then new knowledge and valid and relevant information for the scientific community, central and state decision-makers, investors and local stakeholders that goes beyond the frontiers of these case studies.

To answer the research questions, bibliographic and documentary research procedures were used, based on sources such as books, published documents, websites, articles published in scientific journals, and on the current situation of the use of PV energy in the world and Angola. This study aims to provide knowledge on the topic of PV to tackle social needs that could be useful in similar situations not only in Angola but also in other developing countries.

The paper is organized as follows. After this introduction, the following section includes data and methods. The results section presents the economic assessment of the PV projects and the sensitivity analysis. In the discussion section, these results are analysed and a sustainable development perspective is brought to the analysis. Finally, the main conclusions are summarized at the end.

DATA & METHODS

This study addresses the case of the possible installation of a PV system to supply electricity to schools and health centres in isolated locations in the regions of Cunene and Huíla in Angola, without access to the electricity grid (off-grid systems). This PV system should be able to replace (at least partially) the use of traditional diesel generators. In this way, the direct economic gains will be calculated by reducing the use of diesel currently used in the generators that supply these facilities.

Schools typically operate between September and July, with school breaks of a week or two over Christmas and Easter. Evening education also plays an essential role, given the importance attached to literacy and the education of young people and adults, which is clear from the Plan for Intensifying Literacy and Education for Young People and Adults published in 2019 [29], so the curve for electricity use should reflect this characteristic. The health posts (smallest units of the national health system) operate uninterruptedly between 8 AM and 5 PM on working days, keeping the equipment to a minimum during periods when there are no patients. **Table 1** outlines the equipment required for the functioning of a school and a health post. These assumptions are based on locally obtained information and an assessment of the needs to ensure acceptable health and school conditions.

Table 1. Characterization of the school and health post

School	Number	Power (W)	Rooms	Work day hours	Work night hours	Non-work hours	Electricity demand day (Wh)[1]	Electricity demand night (Wh)[2]	Electricity demand non-work (Wh)[3]	Total Wh/day
Light bulbs room	10	11	5	0	5	0	0	2750	0	2750
Light bulbs lab	10	11	1	4	2	0	440	220	0	660
Light bulbs library	10	11	1	0	5	0	0	550	0	550
TV	2	90	2	2	2	0	720	720	0	1440
Computers	20	180	1	4	2	0	14400	7200	0	21600
Printer	1	120	1	1	1	0	120	120	0	240
Photocopier	1	180	1	1	1	0	180	180	0	360
Fridge	1	150	1	9	5	10	1350	750	1500	3600
Total							17210	12490	1500	31200
Health post										
Light bulbs	5	11	2	9		0	990	0	0	990
Computer	1	180	1	9		0	1620	0	0	1620
Printer	1	120	1	1		0	120	0	0	120
Photocopier	1	180	1	1		0	180	0	0	180
Fridge	1	150	1	9	5	10	1350	750	1500	3600
Total							4260	750	1500	6510

[1] 08:00-17:00 [2] 17:00-22:00 [3] 22:00-08:00

Figure 1 shows the estimated monthly electricity demand for the school and health post, calculated from a the assessment of the required equipment and taking into account school breaks. **Figure 1** also shows the average load factor for a PV unit for electricity production, calculated from [30]–[32] for the locations of Ombadja-Cunene and Lubango-Huíla.

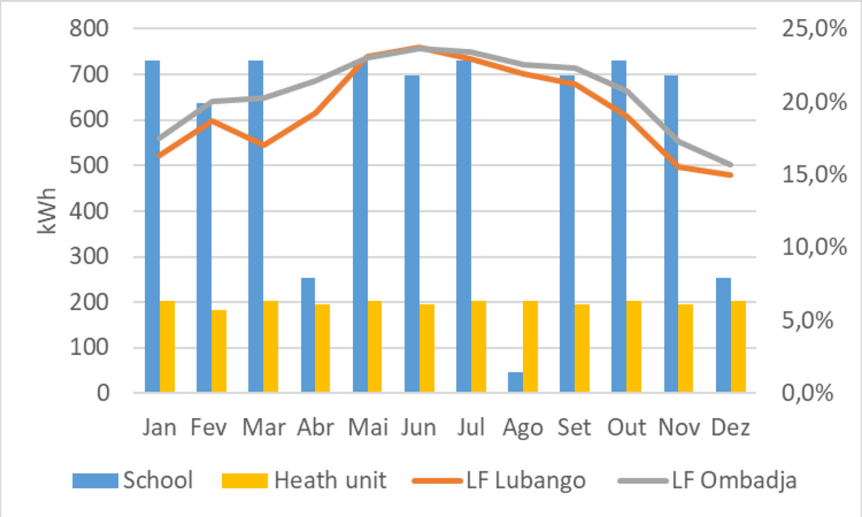

Figure 1. Monthly load factor

Figure 2 shows the hourly electricity demand for the school and health centre on a typical working day, and the equipment's operating regime. The hourly load factor for the PV unit is also presented with information obtained from [30] for two typical days (15 January and 15 June) for the locations of Ombadja-Cunene and Lubango-Huíla.

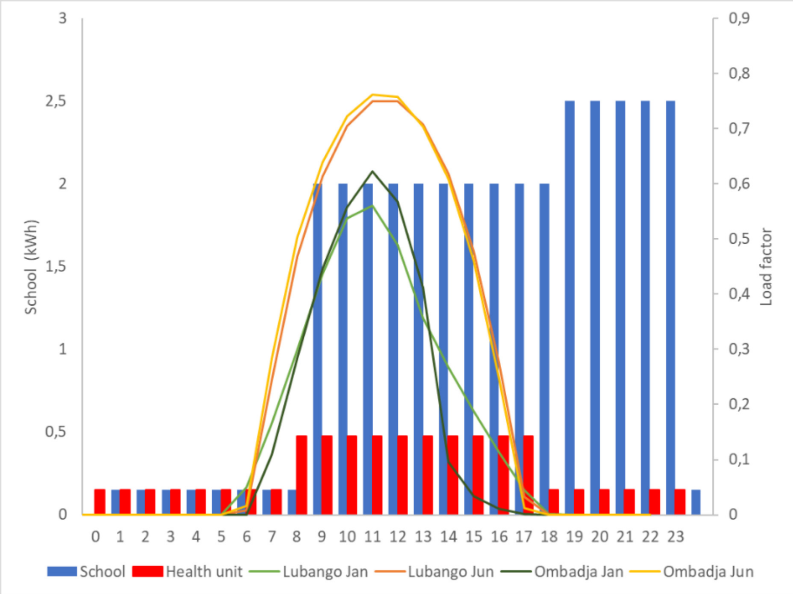

Figure 2. Hourly load factor

The figures show that the school's consumption tends to be higher at night, primarily due to the need for lighting to fulfill the educational objectives for both young people and adults. At the health post and school, there is minimal consumption during non-working nights and weekends, primarily attributed to the necessity of refrigerating perishable goods.

Table 2 summarizes the six scenarios analysed, three scenarios in Ombadja-Cunene and three scenarios in Lubango-Huíla. All scenarios assume that PV unit would partially replace diesel generation.

Table 2. Description of the assumed scenarios

	Scenario 1	Scenario 2
Lubango School	Installation of a 4.5 kW PV unit that supplies more than 96% of daytime electricity needs during one year.	Installation of a 4.5 kW PV unit combined with 3.5 kWh lithium-ion batteries to supply more than 96% of daytime electricity needs and more than 24% of night-time electricity needs during one year.
Ombadja School	Installation of a 4.5 kW PV unit that supplies more than 98% of daytime electricity needs during one year.	Installation of a 4.5 kW PV unit combined with 3.5 kWh lithium-ion batteries to supply more than 98% of daytime electricity needs and more than 31% of night-time electricity needs during one year.
Lubango Health Post	Installation of a 1.2 kW PV unit that supplies more than 96% of daytime electricity needs during one year.	Given the size of the case, the possibility of batteries was not considered.
Ombadja Health Post	Installation of a 1.2 kW PV unit that supplies more than 97% of daytime electricity needs during one year.	Given the size of the case, the possibility of batteries was not considered.

The values for the PV investment costs and diesel generator efficiency were collected from local information and assumed to be 5826 EUR for the case of 4.5 kW installed power and 3255 EUR for the case of 1.2 kW installed power.

Diesel prices (0.150 EUR/L) came from [33] and battery prices (526 EUR) came from [34]. The economic viability of the investment was calculated using the net present value (*NPV*) indicator, calculated by adding up the financial flows (cash flow) updated over the 20-year lifespan, as shown in eq. (1). It was assumed that batteries would be replaced after 10 years of operation and the diesel generator efficiency was set as 30%. The negative flows correspond to the necessary investments (PV unit and battery) and the positive flows correspond to the avoided costs (avoided diesel purchases).

$$NPV = \sum_{t=0}^{20} \frac{CF_t}{(1+i)^t} \quad (1)$$

where *CF* represents cash flow, *i* discount rate and *t* the time life of the project.

Beyond the economic analysis, the avoided emissions from the reduction in diesel use were also quantified. An emission factor of 0.733 gCO_2/kWh was assumed for diesel generation [35].

RESULTS

Table 3 summarizes the results obtained for each scenario under the assumed conditions including the *NPV* for a discount rate equal to 5%, the avoided electricity production from diesel and the avoided CO_2 emissions.

Table 3. *NPV* and avoided CO_2 emissions for each scenario

	Scenario 1 Lubango School	Scenario 1 Ombadja School	Scenario 2 Lubango School	Scenario 2 Ombadja School	Scenario 1 Lubango Health Post	Scenario 1 Ombadja Health Post
Avoided electricity from diesel (kWh/year)	3642	3713	4420	4700	1155	1168
Avoided CO_2 from diesel (kg/year)	2.67	2.72	3.24	3.45	0.85	0.86
NPV (EUR)	-3601	-3558	-3975	-3804	-2530	-2522

For all the cases considered, the *NPV* is negative, indicating that the project is not economically viable under the assumed conditions. Additionally, it was necessary to analyse the risks of implementing PV technology in Angola, particularly in these southern regions, in order to anticipate surprises and ensure that the project is well prepared for adversity. It should be emphasised that the risk analysis in this project for the southern region should not paralyse the implementation of the project because it identifies possible adversities. On the contrary, its function is to ensure that the objectives are achieved by mapping the challenges and offering alternatives to avoid them or reduce the impacts, given that this is a study area with enormous difficulties in implementing a project of such magnitude.

Given this uncertainty, a few simulations were conducted to analyse the sensitivity of the results against the assumptions made. The following simulations were considered for the different cases analysed.

- Variation in the discount rate of 5% and 10%, to analyse how the discount rate could affect the economic viability of the projects;
- Variation in the cost of the PV system, with a 25% compared to the base scenario, taking into account that the capital cost of PV modules will tend to reduce with market growth and greater experience in the sector [36];
- Variation in the price of diesel, up to four times higher than that assumed in the base scenario. The country ranks fourth among the countries with the lowest diesel prices given the existing fuel subsidies, with neighbour countries charging values at least six times higher [37].

Figure 3 presents these simulations for a deterministic "what-if analysis" combining different conditions. In each table, the base case scenario is highlighted in grey on the top cell.

Lubango school **Ombadja school**

Scenario 1 diesel vs. discount rate

NPV (EUR)	0.15	0.3	0.45	0.6
5%	-3601	-1376	849	3075
10%	-4306	-2786	-1266	254

NPV (EUR)	0.15	0.3	0.45	0.6
5%	-3558	-1290	979	3247
10%	-4276	-2727	-1177	372

Scenario 2 diesel vs. discount rate

NPV (EUR)	0.15	0.3	0.45	0.6
5%	-3975	-1275	1426	4126
10%	-4711	-2866	-1021	824

NPV (EUR)	0.15	0.3	0.45	0.6
5%	-3804	-933	1938	4810
10%	-4594	-2632	-671	1291

Scenario 1 diesel vs. investment

NPV (EUR)	0.15	0.3	0.45	0.6
-5826	-3601	-1376	849	3075
-4369	-2144	81	2306	4532

NPV (EUR)	0.15	0.3	0.45	0.6
-5826	-3558	-1290	979	3247
-4369	-2101	167	2436	4704

Scenario 2 diesel vs. investment

NPV (EUR)	0.15	0.3	0.45	0.6
-6352	-3975	-1275	1426	4126
-4895	-2518	182	2883	5583

NPV (EUR)	0.15	0.3	0.45	0.6
-6352	-3804	-933	1938	4810
-4895	-2347	524	3395	6267

Lubango health post **Ombadja health post**

Scenario 1 diesel vs. discount rate

NPV (EUR)	0.15	0.3	0.45	0.6
5%	-2530	-1824	-1119	-413
10%	-2753	-2271	-1789	-1307

NPV (EUR)	0.15	0.3	0.45	0.6
5%	-2522	-1808	-1095	-382
10%	-2748	-2260	-1773	-1286

Scenario 1 diesel vs. investment

NPV (EUR)	0.15	0.3	0.45	0.6
-3235	-2530	-1824	-1119	-413
-2426	-1721	-1015	-310	396

NPV (EUR)	0.15	0.3	0.45	0.6
-3235	-2522	-1808	-1095	-382
-2426	-1713	-999	-286	427

Figure 3. Sensitivity analysis

This analysis was complemented with stochastic economic investment assessment using a Monte Carlo Simulation (MCS) methodology applied to each one of the scenarios and combining the three uncertain factors to obtain the probabilistic distribution function (pdf) for the *NPV*. For the sake of simplicity and given the lack of historical information, for both discount rate and diesel prices triangular distributions were assumed where the minimum, the most likely, and the maximum values were defined and given to the system. As for the cost of the PV system, a uniform distribution was chosen given the minimum and maximum values, with all having an equal chance of occurring. **Table 4** summarizes the results of the MCS and the main graphs are presented in Appendix.

Table 4. Monte Carlo Simulation

	Scenario 1	Scenario 2
Lubango School	Mean = -525 EUR Standard deviation = 1247 EUR Probability *NPV* positive = 33.3%	Mean = -333 EUR Standard deviation = 1475 EUR Probability *NPV* positive = 40.6%
Ombadja School	Mean = -436 EUR Standard deviation = 1275 EUR Probability *NPV* positive = 35.6%	Mean = 19.3 EUR Standard deviation = 1549 EUR Probability *NPV* positive = 49.2%
Lubango Health Post	Mean = -1067 EUR Standard deviation = 489 EUR Probability *NPV* positive = 0.2%	
Ombadja Health Post	Mean = -1381 EUR Standard deviation = 445 EUR Probability *NPV* positive = 0%	

The results show that the economic viability of the projects is particularly difficult to reach for the cases of small health posts. Even in the case of schools, some of the scenarios still show a negative *NPV*. However, the sensitivity analysis demonstrates that a positive *NPV* may be reached if the real cost of diesel is considered and if the investment costs can be reduced. With the current subsidised diesel prices, it is extremely difficult to justify investments that seek to reduce the consumption of fossil fuels. Subsidies for diesel represented in 2022 more than 70% of the diesel total cost in Angola [38]. The Tornado charts, presented in the Appendix, highlight the importance of the diesel price as the most relevant of the uncertainty factors considered in the analysis.

DISCUSSION

The result from this research and in particular the low economic viability is not an expected outcome, as previous research has addressed the issue of diesel fuel subsidies and demonstrated that PV systems with batteries can only become cost-competitive at higher diesel fuel prices. In these cases, high renewable shares may be achieved in the systems. [39]. In Angola, the diesel price is so low that diesel generators remain economically superior to PV systems with or without batteries. Diesel prices would need to be about three times the current value for PV systems to become economically attractive. Despite the negative values obtained for the base case scenario, the sensitivity analysis shows that lowering investment costs for either PV systems or batteries opens fundamental opportunities for the sector, mitigating the effects of low diesel prices. The issue of batteries and the potential for using second-life options is discussed in the literature [45], highlighting this as a promising avenue for rural communities that frequently experience grid outages.

It is important then to mention that the interest of these projects goes much beyond a purely economic analysis and the potential contribution to the sustainable development of the regions should not be overlooked. Although major attention is given to the economic side of energy reforms, the development envisaged is essential for the sustainable growth of the economies, especially for developing countries and must balance economic, social, and environmental interests [9].

Table 3 already presents a first attempt to quantify avoided emissions for each project, highlighting the significant role they may play in the dissemination of PV technology and the increasing demands of both the education and health sectors. These CO_2 emissions can be seen as a proxy for other pollutants, as generators are substantial contributors to environmental and health burdens in Sub-Saharan Africa [40].

Contribution to Sustainable Development in Sub-Saharan Africa

According to [15] report, 60% of healthcare facilities in Africa lack access to electricity and 90% of children in Sub-Saharan Africa go to primary schools that lack electricity. This highlights the importance of achieving a reliable electricity supply to ensure quality social services. United

Nations [41] study also showed that electricity access interventions in rural areas tend to increase income and consumption expenditure, which will lead to positive educational outcomes and positive impacts on health and gender empowerment.

We argue then that the interest of this project goes far beyond direct economic issues, with significant gains from an environmental and social point of view. Other non-economic gains include the potential to generate employment and improve the current situation of the region. These projects may have a direct impact not only on jobs related to the PV sector but also on other non-related sectors that will benefit from education and health improvements for the populations. Moreover, the growth of a market in the country could result in significant gains in scale, making these investments viable in the near future, benefiting from the quality of the country's solar resources and bringing important economic advantages for the all country.

In the education and health sectors, the social gains are evident. For example, in Angola around 42% of the women and 16% of the men are illiterate [42] as a result of various factors and energy access in schools is fundamental to tackling this challenge. This gender gap is also evident in Sub-Saharan Africa in general, as 72.5% of males were literate in 2020 and the share among females was measured at 59.4% [43]. Microgeneration with PV technology will make it possible to take advantage of evening classes for adult education. This should improve education levels, lower the levels of illiteracy in the country and contribute to reduce the gender gap, particularly in the localities under study.

As for the health sector, access to minimum health services is still far from being available to all the population [42] and access to a reliable electricity system is fundamental to providing primary health care and ensuring the safe storage of medicines. In Angola, maternal and child mortality continues to be a major challenge to be overcome. Maternal mortality has been declining, but it still stood at 199 deaths per 100,000 live births in 2022 [44] and for the same period, the child mortality rate was 55.8 [45]. This can be explained by the fact that prenatal care coverage is 92% in urban areas and is decreasing to 63% in rural areas. On the other hand, 18% of women in Angola do not take any prenatal consultations. In addition, only 46% of births occurred in a sanitary facility, 44% in the public sector, and 53% occurred at home. Only 50% of births are assisted by a qualified healthcare professional. It is also worth noting that the days after delivery are a critical phase in the lives of mothers and their newborns, but only 23% of women receive a post-neonatal consultation within the first two days of delivery, and 62% do not receive any postpartum consultation. Only 21% of newborns had a post-neonatal consultation in the first two days after birth [46]. Again, numbers for Saharan Africa in general show also a similar concern, 223 maternal deaths per 100,000 live births in 2020 [47] and a child mortality rate of 71 deaths per thousand births in 2020 [48].

Despite Angola's national vaccination calendar covering all vaccines for routine immunization of children, according to the World Health Organization (WHO), immunization coverage has seen a general decline since 2018–2019 for multiple vaccines, which was further aggravated by the COVID-19 pandemic in 2020. In 2021, the vaccination coverage rate in Angola was around 60%, with the exception of BCG and measles vaccines, which presented coverage rates of 79% and 40%, respectively. The main challenge to routine immunization identified was the shortage of vaccine stock at the regional level. There are logistical challenges that result in regional shortages in municipal health units. These challenges include late communications about reduced stocks and transportation costs, especially for communities with difficult accessibility [44].

Angola presents, as many other developing countries, a very high mortality rate attributed to household and ambient air pollution [49]. Emissions from diesel backup generators are a major problem in Sub-Saharan Africa and contain toxic air contaminants, including many known or suspected cancer-causing substances, such as benzene, arsenic, and formaldehyde [50], [51].

In most Sub-Saharan Africa, diesel generators for schools and health units are used in close proximity to the children and other facilities users frequently already suffering from pathologies or presenting special needs such as newborns, pregnant or postpartum women, which creates additional health risks in a population already severely deprived. Therefore, implementing decentralized PV technology in the country can make a significant contribution to improvement of the health and education system but also from improvement of air quality with the replacement of old diesel generator units. This should result on the overall reduction not only of greenhouse gas emissions but also other pollutants caused by the excessive use of diesel in generator sets, especially in sensitive areas namely health facilities and schools.

We can highlight then the obvious contribution of these PV off-grid projects towards SDG 7 (Affordable and Clean Energy), SDG 4 (Quality Education), SDG 3 (Good Health and Well-being) but the systemic nature of these SDG confirm that reliable access to energy is also a fundamental enabler to achieving other goals, for example food security, zero hunger no poverty [52], [53]. Moreover, industrial development, better working conditions, and economic growth are also highly dependent on a reliable energy system, as well as the higher academic level of the population and their overall health.

It is worth noting out that among the 17 SDGs, Angola has only achieved 2, which are Responsible Consumption and Production (12) and Action Against Global Climate Change (13). Life in Water (14), and Partnerships and Means of Implementation (17) are ongoing significant challenges. The remaining SDGs are considered major ongoing challenges for the country requiring profound interventions, with most of them highly dependent on secure access to electricity [54].

In alignment with these sustainability concerns, the National Development Plan of Angola [55] clearly demonstrates the importance of a reliable access to energy to improve Angola's performance in each SDG. This is evident through plans to enhance and expand the solar-powered cold chain, including equipment for temperature control to improve vaccination rates, promoting nationwide energy distribution licenses through off-grid systems for rural electrification, and facilitating access to clean energy sources to limit exposure to pollutants with high health impacts. Additionally, plans involve the expansion of schools and improvements in their facilities. Furthermore, the National Plan for Sanitary Development [56] identifies health needs and current issues, including the poor maintenance of health units and reduced access to drinking water, sanitation, and energy and underlines the need to ensure reliable energy access to health units.

CONCLUSIONS

PV solar energy is growing fast in developed and other developing countries. If on one hand, this is driven by the concerns about the reduction of greenhouse gases, on the other hand, the expected reduction of investment costs and the potential to install distributed off-grid facilities are important strengths of this technology. Overall, a steady growth trend is expected over the next few years, which can be interpreted as solar energy becoming increasingly competitive in different countries around the world.

PV is still in an early stage of development in most Sub-Saharan Africa and important institutional, regulatory and cost barriers still exist. However, this technology could bring significant benefits for the populations living in remote regions, with no access to the public grid and requiring basic social services. There are therefore several reasons to encourage the implementation of PV energy in these regions in particular directly or indirectly related to the SDG, namely the low electrification rate and limited access to the central grid. The wide dispersion of the population in rural areas makes it costly to extend the existing electricity networks, with difficult to access to certain localities. Additionally, while current electricity consumption is low, it tends to increase significantly in the next years underlying the importance of benefiting from the high PV electricity potential, and the contribution of these projects to responding to urgent social problems related to education and health and to improving the living conditions of the population.

This study addressed the case of health posts and schools, analysing the economic viability of off-grid PV systems that would partially replace diesel generation for the case of Angola. The results indicate the projects are still difficult to justify under a purely economic analysis. This is mainly due to the still high CAPEX and highly subsidized diesel costs. However, the interest of these projects goes much beyond their economic value and their contribution to the sustainable development of the country and these less favoured regions is evident with important gains related to health, education, gender empowerment and job creation.

With regard to the SDGs related to the proposed photovoltaic microgeneration in schools and health facilities, Good Health and Well-Being (3) and Quality Education (4) should be highlighted in more detail, as they should be directly benefited by these projects. The child mortality rate in Angola remains high, and the absence of vaccines for different pathologies has concerned the responsible entities since there are targets to be achieved by 2030. The implementation of microgeneration with PV technology should improve the conditions of health care and vaccine storage units, thereby contributing to the reduction of maternal and child mortality rates. SDG 4 (Quality Education) aims to ensure access to inclusive, quality, and equitable education and to promote lifelong learning opportunities for all. However, education in Angola has not yet achieved the expected results, and this objective remains one of the country's main ongoing challenges. Thus, the implementation of this technology should improve the conditions of schools, thereby contributing to an increased participation rate in organized pre-school learning, an increased net rate of enrolment in primary school, and an increased literacy rate [54].

Although the case of Angola was central to this research, the scientific contribution of the work is expected to extend beyond this case and allowed to support the initial hypothesis. The proposed approach should facilitate the analysis of renewable energy projects in different systems by showing the relevance of addressing governmental conditions (such as fossil fuel subsidies) and the need to consider a holistic sustainability perspective. This perspective should embrace not only economic viability and SDG 7 but also the specific social needs of developing regions. This approach and the results can then be used to support the development of well-founded pathways for defining sustainable energy policies and plans for these regions.

In conclusion, this research focused on the project evaluation perspective quantifying financial costs and benefits and avoided CO_2 emissions and qualitatively addressing the potential social gains of the projects. This study comes to pave the way for further investigations to support central and local government policies; including the need to expand the study towards a cost-benefit analysis to quantify and valuate the social value of health based for example on the concepts of value of a statistical life [57] or the social value of education [58].

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APPENDIX: Monte Carlo Simulation

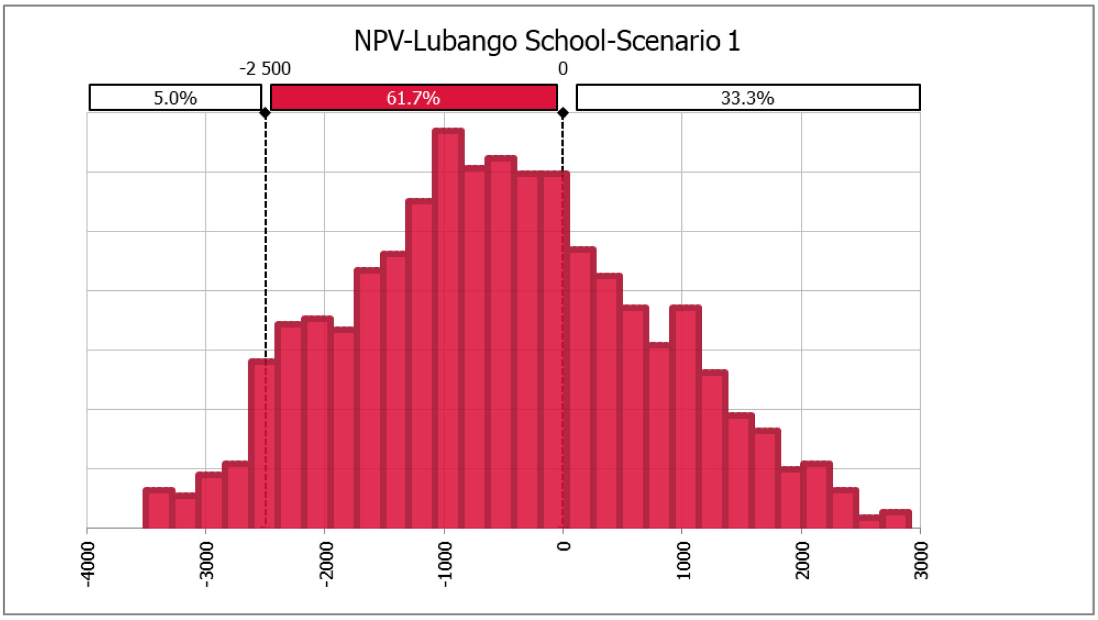

Figure 4. Probability distribution function for the Lubango School-Scenario 1

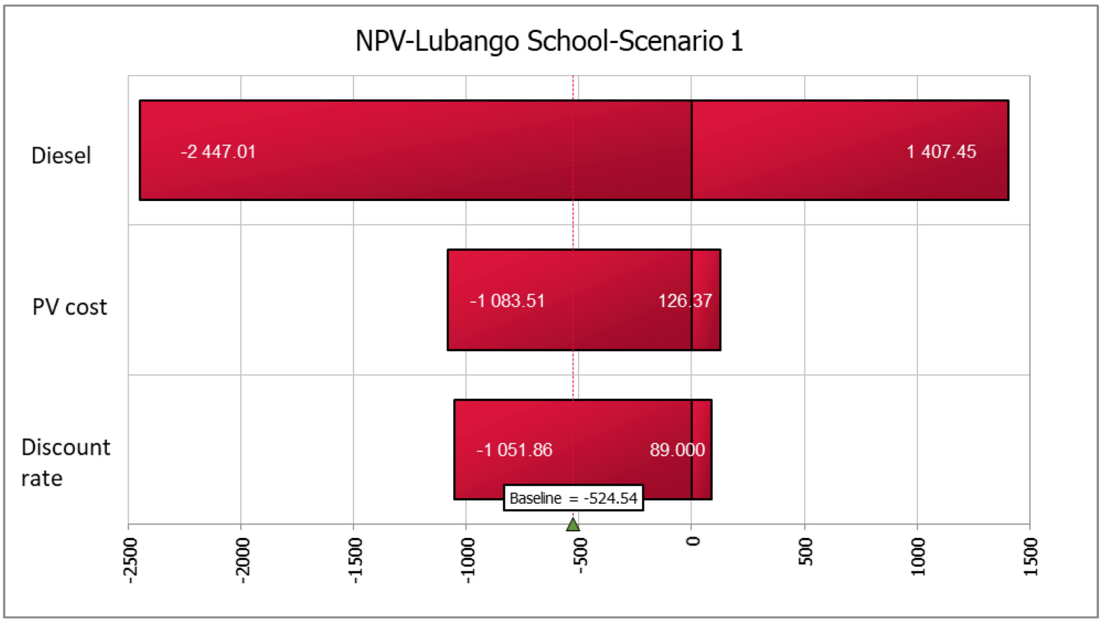

Figure 5. Tornado chart for the Lubango School- Scenario 1

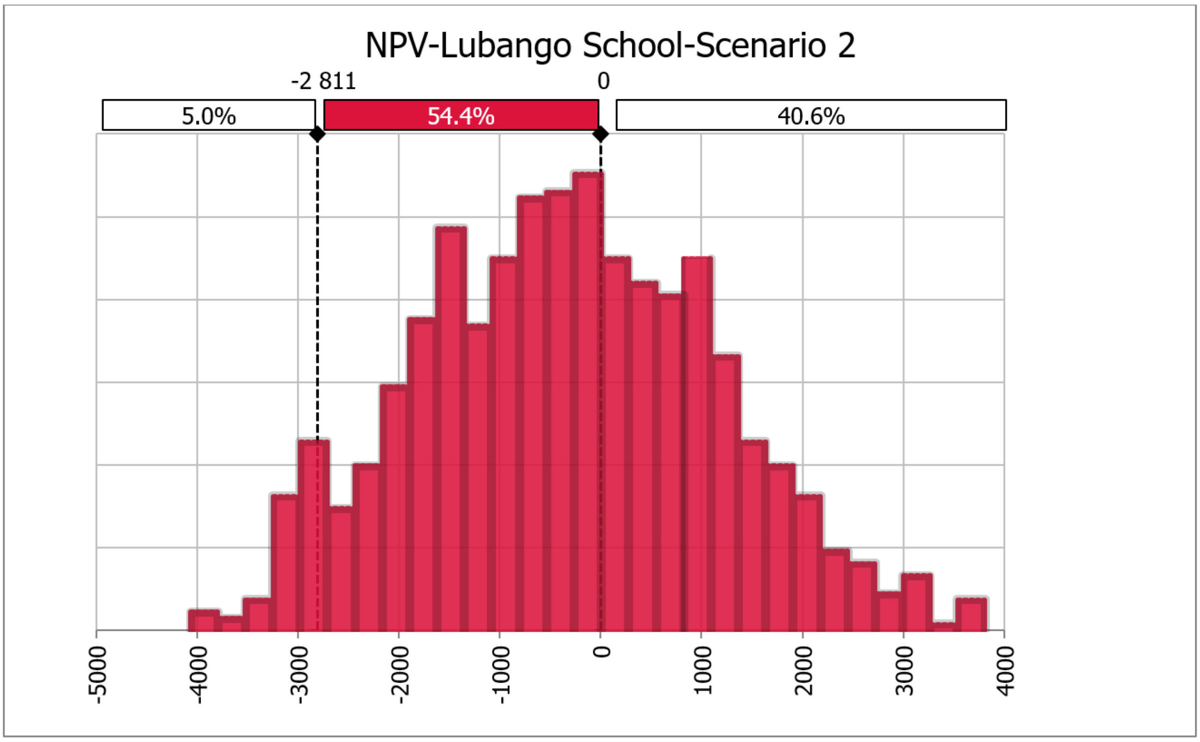

Figure 6. Probability distribution function for the Lubango School-Scenario 2

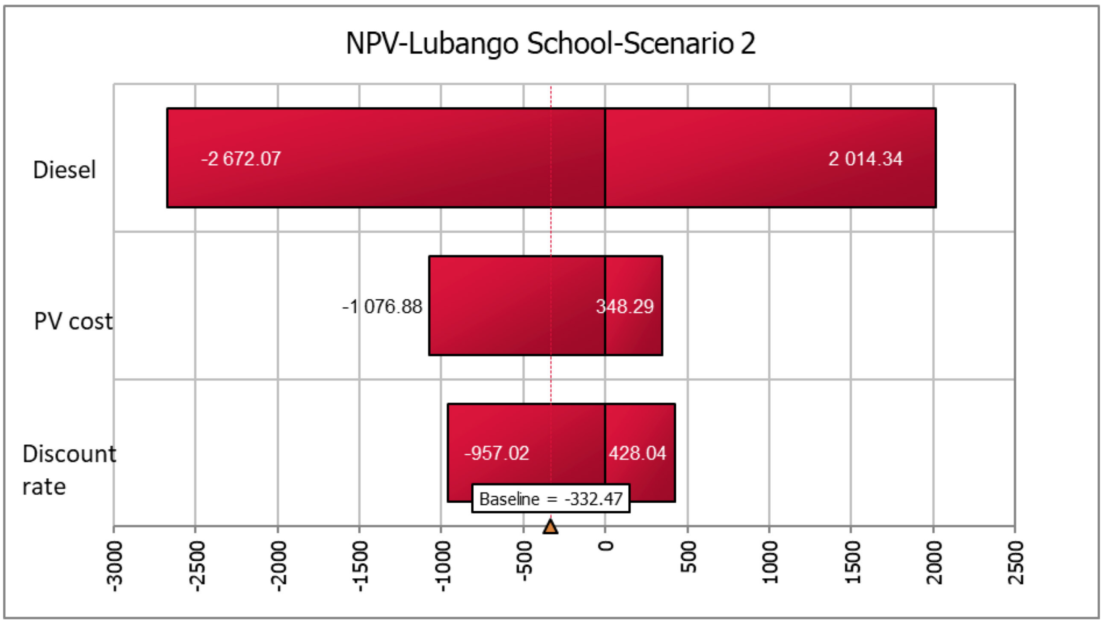

Figure 7. Tornado chart for the Lubango School-Scenario 2

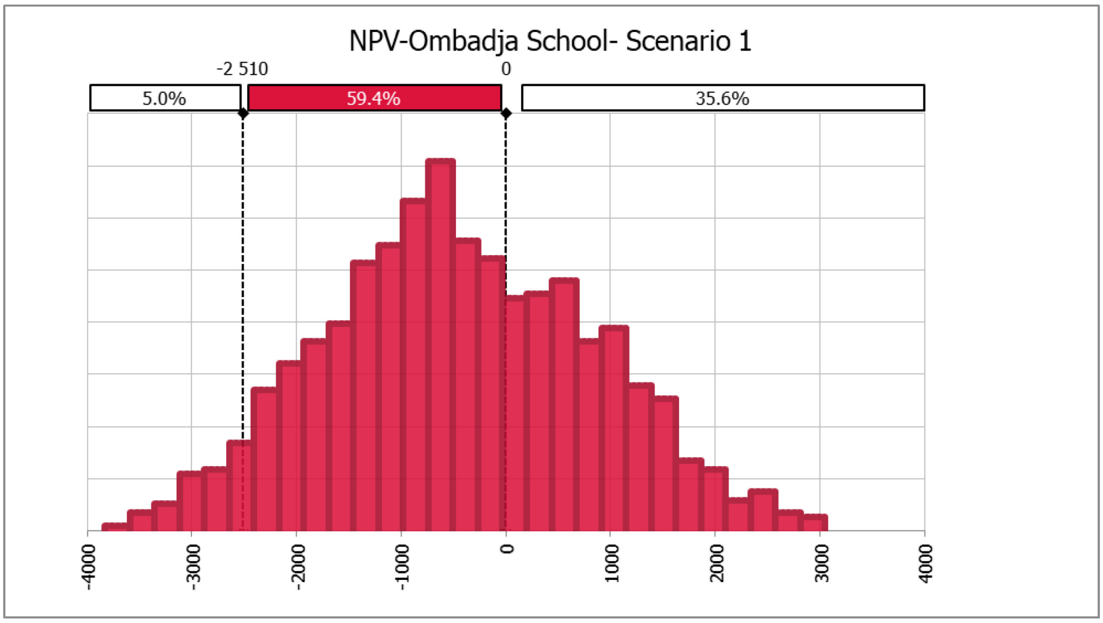

Figure 8. Probability distribution function for the Ombadja School-Scenario 1

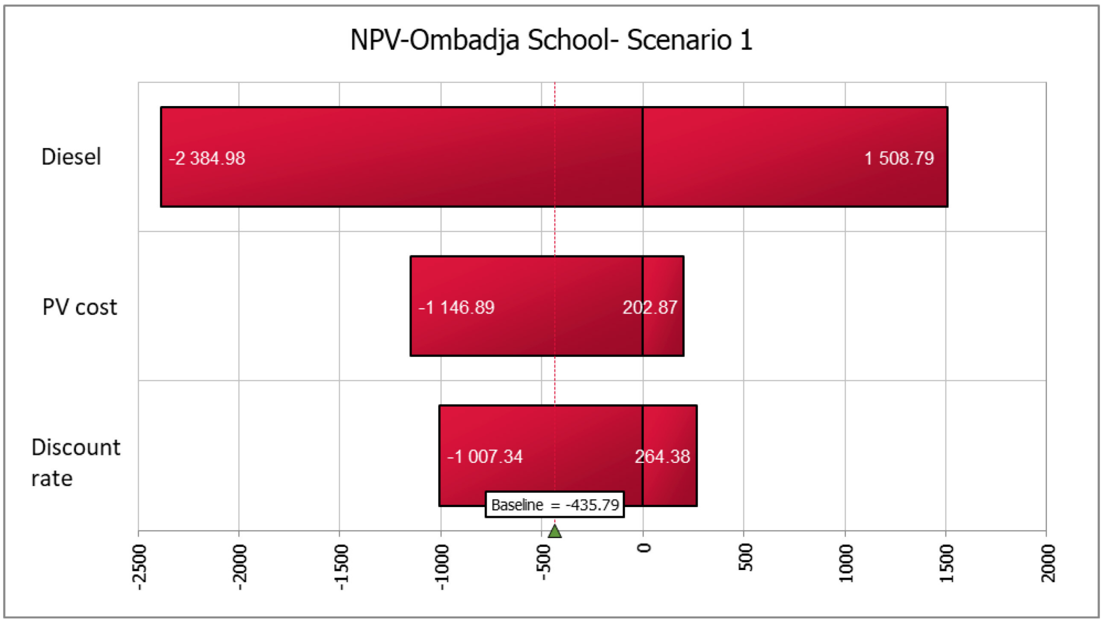

Figure 9. Tornado chart for the Ombadja School- Scenario 1

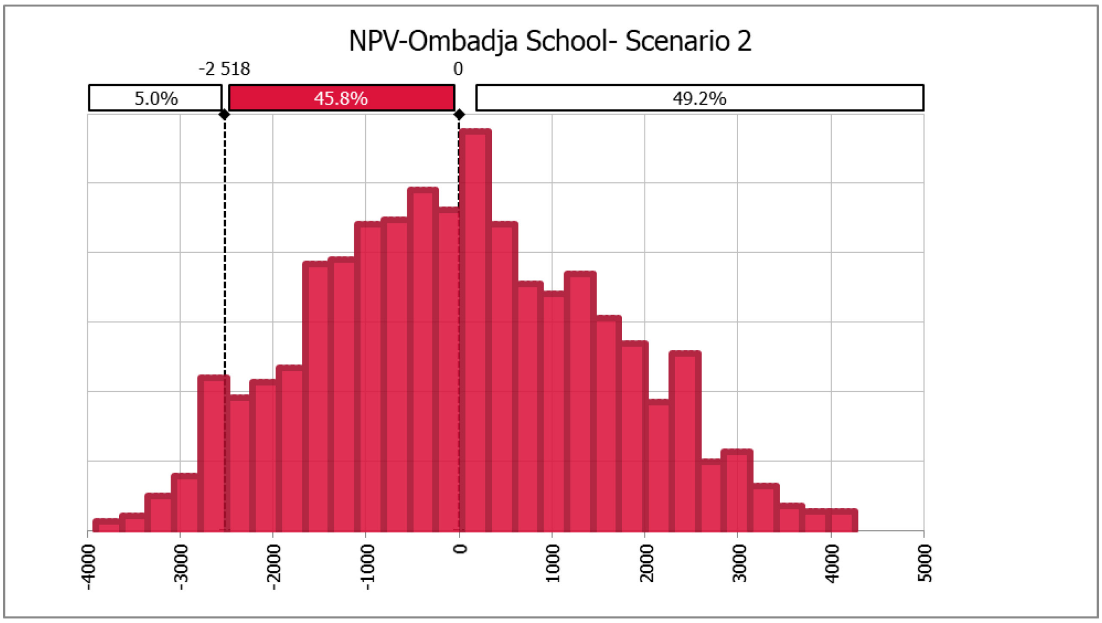

Figure 10. Probability distribution function for the Ombadja School-Scenario 2

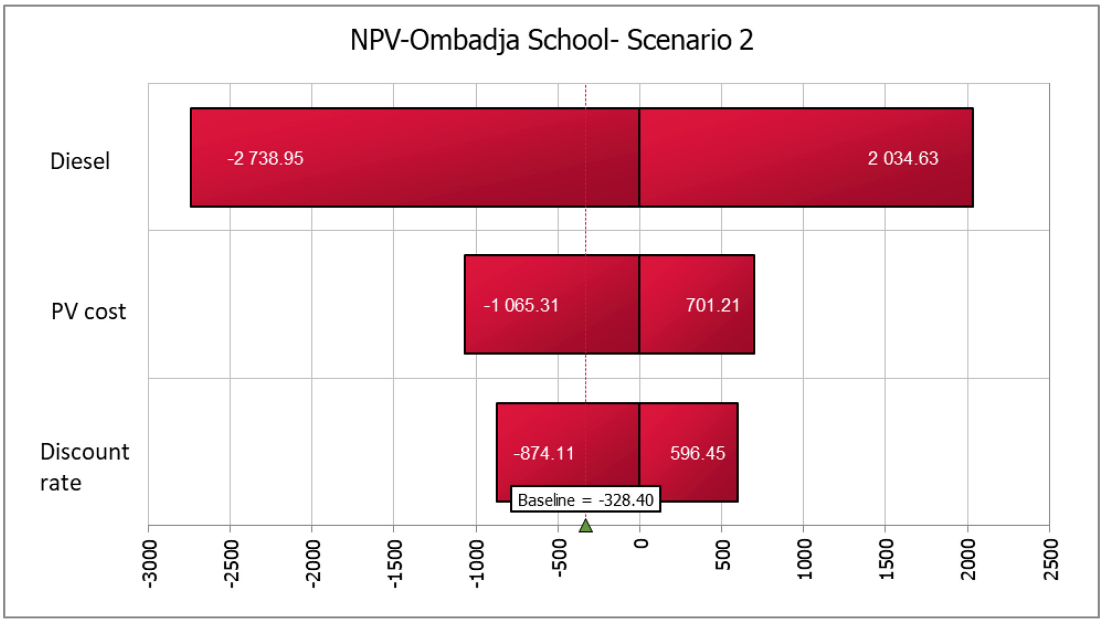

Figure 11. Tornado chart for the Ombadja School-Scenario 2

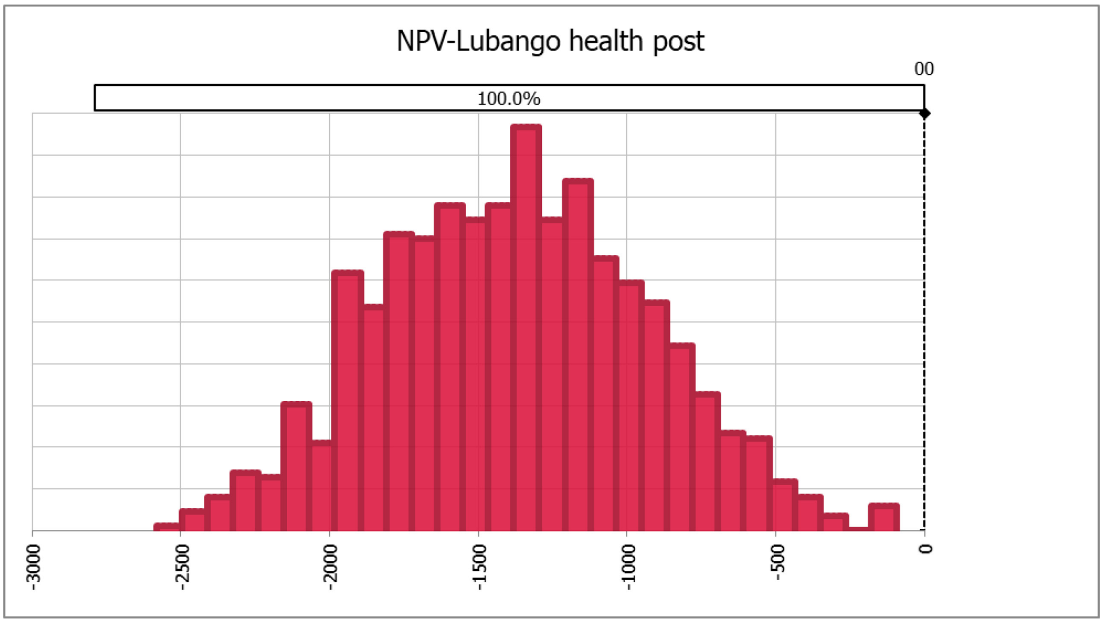

Figure 12. Probability distribution function for the Lubango health post

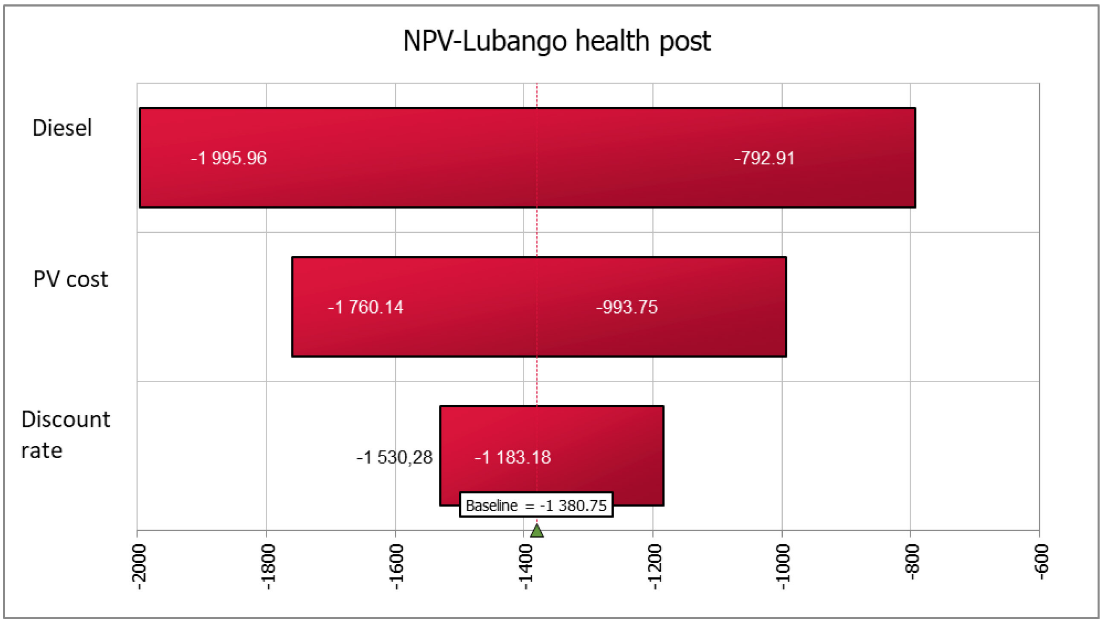

Figure 13. Tornado chart for the Lubango health post

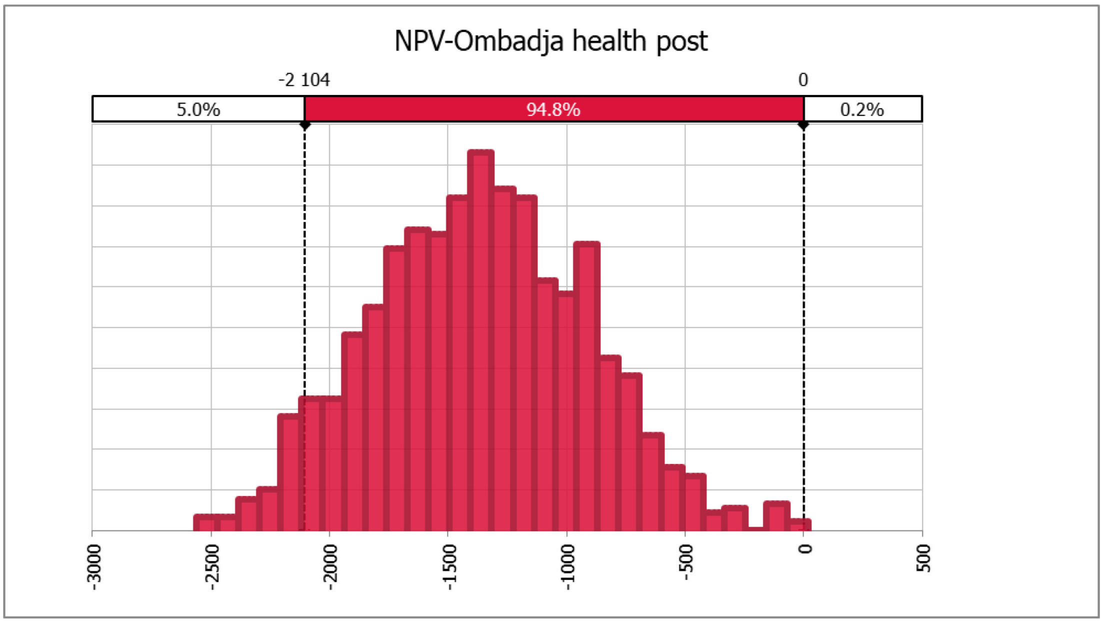

Figure 14. Probability distribution function for the Ombadja health post

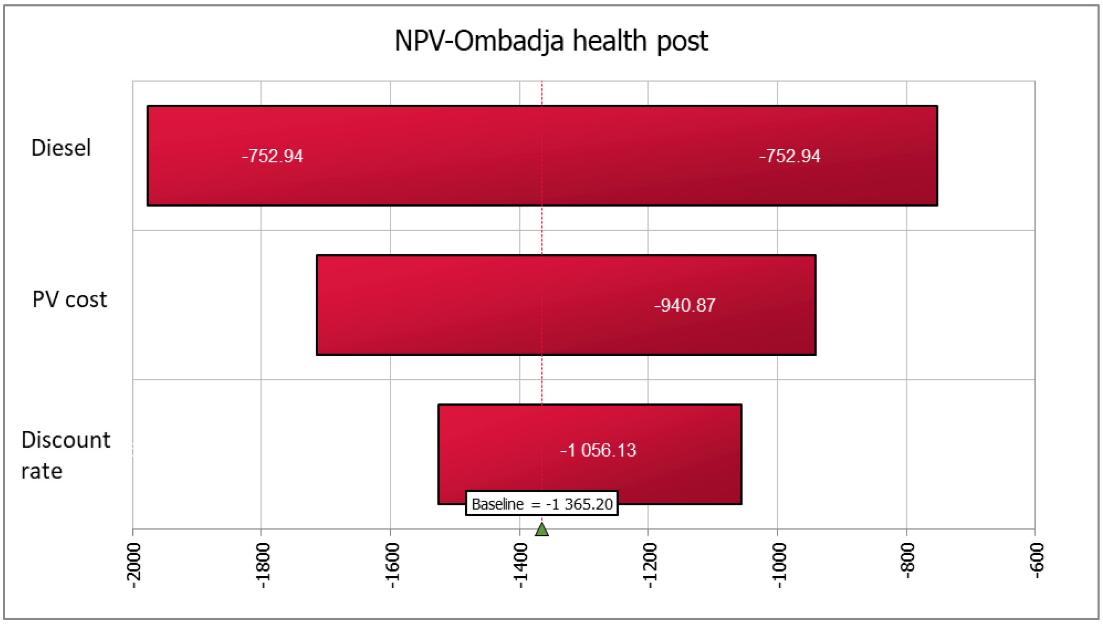

Figure 15. Tornado chart for the Ombadja health post

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