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Sustainability Assessment of the Bui Hydropower System

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Abstract: Sustainable hydroelectric projects are judged by their contribution to sustainable development, long-term viability, and ability to integrate sustainability goals. This paper analyses the Bui hydroelectric dam in Ghana vis-à-vis these expectations using sustainability indices. A multi-criteria analysis tool, APIS (Aggregated Preference Indices System), is used to build indices for Bui dam for four hydrologic seasons. An analysis of the indicators used revealed that environmental indicators are weightiest and economic indicators have the least weight. Comparative analysis of the Bui dam project shows 40%, 36%, 18%, and 6% priority for technical, economic, social, and environmental criteria, respectively, during its implementation stages. Per estimation of this work, the general sustainability index of the Bui dam is between 0.4 and 0.6 on a scale of 0 to 1. The impact of seasonal climate change will reduce the index to below 0.5 for three hydrologic seasons. The results show that Bui dam has an average but weak index of sustainability. Multi-criteria analysis offers quality assessment of energy projects, which is valuable for analyzing proposed or existing energy projects. This paper shows the possibility of using multi-criteria analysis approach to assess the sustainability of a hydroelectric dam. The approach offers a quantitative and qualitative assessment of a hydroelectric dam via a suitable choice of indicators.

Keywords: Aggregated Preference Indices System (APIS); Bui dam; Ghana; multi-criteria decision analysis; sustainable development; sustainability index

1. Introduction

Sustainability has become a major issue for discussion in all fields around the world. The idea has notably gained ground in the energy sector. The availability and source of energy alternatives has become critical for major energy and energy policy decisions. Energy policymaking, however, is interwoven with social, economic, environmental, technical, and national issues [1–3], which represent conflicting demands. Sustainable energy policy integrates the social, economic, environmental and technical issues for a common energy development goal [4,5]. The sustainability of an energy system is, therefore, judged by its ability to meet strict social, economic, environmental, and technical criteria [6,7]. Social sustainability measures the social acceptance of the energy system, quality of life, and the impact the available energy service may have on social well-being [8,9]. Economic sustainability measures how energy use and production pattern, as well as the quality of energy services, affect progress in development [9,10]. Environmental sustainability measures the impact the energy alternative has on the overall environment. Technical sustainability measures the availability and the technical efficiency of the available energy service [11]. Integrating each of these criteria posed a significant challenge in the past but has been overcome by the emergence of multi-criteria analysis methods. Thus, a multi-criteria analysis approach has proven effective in integrating effects of social, economic, environmental, and technical aspects of energy systems. In a multi-criteria analysis of energy systems, criteria are usually defined in such a way that they reflect a sustainability concept that is based on a strategic viewpoint and timely information, etc. [12,13]. In order to further simplify the process of multi-criteria analysis, criteria must be defined by the use of sub-criteria (or indicators) that will define clear sustainability goals [12,13]. By so doing, we create a complex (multi-attribute, multi-dimensional, multivariate, etc.) system whose qualities under investigation are then determined by many initial indicator values [12]. With an appropriate mathematical formulation, individual indicator values are aggregated into a single number (sustainability index) that becomes the basis for judging the quality of the energy system. The sustainability indices are used as a means for monitoring the quality of an energy system and as a quantitative measure of an energy system's quality. Multi-criteria analysis approach has therefore played a significant role in developing, describing, and simplifying the concept of sustainability.

The concept of sustainability has widened in scope with the major introduction of Sustainability Development Goals (SDGs). The 17 SDGs and the 169 targets are to build on the achievements of the Millennium Development Goals (MDGs) and complete what they could not achieve by 2030 [14]. The goals focus on areas such as people, planet, prosperity, peace, and partnership [14]. The SDGs are targeted to benefit all people. SDG 7 is dedicated to ensuring access to affordable, reliable, sustainable, and modern energy for all [14]. SDG places emphasis on promoting renewable energy, energy efficiency, and clean energy. In this paper, we assess the Bui dam in view of sustainability issues regarding the planning, construction, and post-construction stages. We will adopt the definition of sustainable development as "development that meets the needs of the present without compromising the ability of the future generation to meet their own needs" [4,5]. We will use a literature review and our own findings to define the needs of the present generation, and SDGs to judge Bui's ability to meet the needs of future generations. We will also use indicators that define the true environmental, social, economic, and technical issues surrounding the planning, implementation, and post-implementation stage

Bui dam construction falls under a regime where dam projects are supposed to meet stricter environmental, social, economic, and technical guidelines. Bui dam's construction formed part of the national projects to expand electricity supply to the northern and central parts of Ghana [15,16]. Locally, the project was to come with good roads, schools, and hospitals, which will boost the local economy [16]. Other benefits expected are: a power supply that will complement Akosombo and Kpong dams in Ghana, potential export of electricity to Burkina Faso, Cote d'Ivoire, and Mali under the West Africa Power Pool Project (WAPP) arrangement, construction of the Bui City and agro-tourism, construction of a fishing harbor and irrigation scheme (30,000 hectares of land), and employment generation for the locals, especially during the construction phase. Before the construction of Bui dam, however, some issues with relevance to sustainable dam development came up. For instance, the social, environmental, and health impacts of the dam on the local population were contested by national and international social and human right activists [17]. Their position was that the negative impacts of the dam were underestimated to make the dam more attractive to international sponsors [17]. The Environmental and Social Impact Assessment's (ESIA) position on climate change impacts on the Bui dam and the global warming potential of the dam were also challenged [18,19]. The Environmental Resource Management (ERM) assumed that the greenhouse gas emissions of the Bui dam would be minor [20]. According to [18], however, the dam will be a major emitter of greenhouse gases, many times worse than a natural gas plant of similar size. Consequently, McCully [18], concluded that the ERM position on the greenhouse gas impact of the Bui dam seems to be a deliberate distortion of reality. Despite these concerns, the government of Ghana pushed ahead with the planning and construction of the Bui hydroelectric plant. Bui dam's project has led to improvements in road networks, drinking water, health, and education. However, according to [16], much still remains to be done to improve the livelihood of the affected communities. Social sustainability analysis by [21], shows that the main social impacts of the Bui Dam were on livelihoods, loss of land, and resettlement of affected people. Farmers have lost significant sections of their farmland and the little land they have is reported to be infertile [16,21]. Fishermen complain that they have been settled far away from the river, making access difficult [16]. Resident fishermen are now in competition with immigrant fishermen for their livelihoods, coupled with the dangerous nature of fishing in the lake [21]. The socioeconomic impact of the dam on the local population has raised concerns about the social and economic sustainability grounds for building the dam. The deliberate attempt to neglect issues of Global Warming Potential (GWP) and environmental impact raises questions about the cleanliness and environmental friendliness of the dam. Finally, the neglect of climate change analysis in the dam design forces us to question the technical sustainability of the dam against future climate change impacts. However, there has been no study to evaluate how the decision to neglect these important social, environmental, and technical issues might impact the dam's quality. More importantly, few studies, if any, are dedicated to assessing a hydroelectric dam by use of a quantitative quality assessment approach with a flexible choice of indicators that define the dam's condition. So even though this study represents local research, the method might be replicated for other regions around the world using the right indicators that define energy conditions.

This study examines how well Bui dam construction considered sustainable dam development standards. The objectives of this article are to identify, select, analyze, and weight indicators used as the basis for developing the Bui hydroelectric dam. The study aims at building sustainability indices (a quality assessment) of this new dam project. It could serve as a baseline study for Bui dam and a method to consider for hydropower sustainability assessment.

2. Study Area

The study focuses on the Bui hydroelectric dam, its environment, and the resettlement communities.

2.1. Bui Hydroelectric Project

The Bui hydroelectric project sits on the Black Volta River, at the border of the Northern and Brong-Ahafo Regions in northwestern Ghana. It's on latitude 8°16′42′′ N and longitude 2°14′9′′ W (Figure 1), between Bole in the Northern Region and Banda in the Brong-Ahafo Region. The project was a collaboration between the government of Ghana and Sino Hydro, a Chinese construction company [15]. Construction of the main dam began in December 2009 and was completed and commissioned in December 2013 [22]. The dam's first generator produced power for the grid on 3 May 2013 [22,23]. Twenty-one percent of the project falls within the Bui National Park [24,25] and all parts of the project lie within Ghana. The project includes a main dam in the Bui gorge and two saddle dams in the neighboring Banda Hills [26]. The project is expected to create a reservoir of 444 km^2, extending about 40 km upstream of the dam. The Bui Power Authority manages the Bui hydroelectric project [16,27]. The dam has a maximum generation of 400 MW at full capacity.

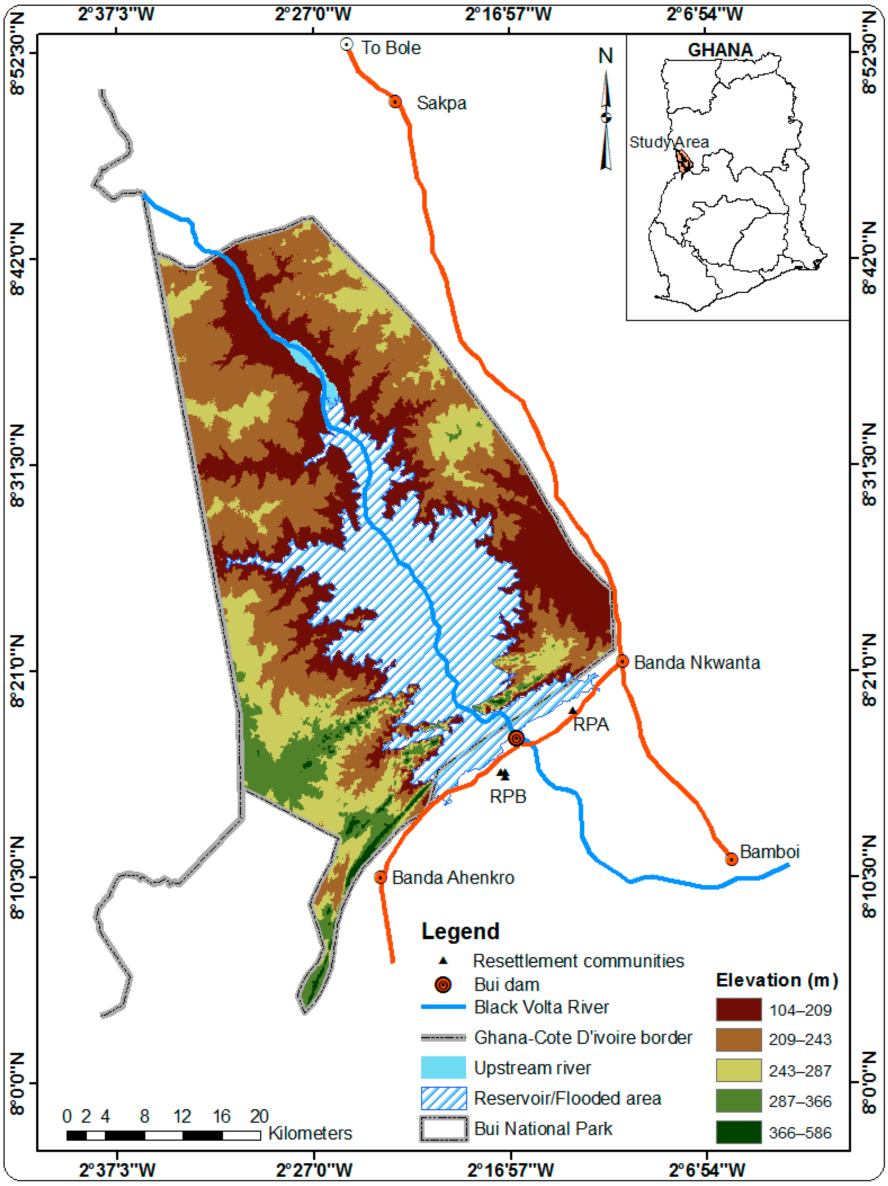

Figure 1. Location of Bui dam and resettlement communities (RPA–Resettlement Part A; RPB–Resettlement Part B).

2.2. Climate

The Bui hydroelectric project area falls within the Guinea Savannah woodland ecological zone under the influence of Sudanese climate characterized by pronounced wet and dry seasons. The wet and dry seasons occur because of the northward and southward motion of the Intertropical Convergence Zone (ITCZ) [28]. Four hydrological seasons occur within the study area: dry season (January–March), pre-wet season (April–June), wet season (July–September), and post-wet season (October–December) [28]. The paper divides the assessment of the Bui dam according to these four hydrologic seasons. The intent is to have a range of numbers that measure sustainability rather than a single number.

2.3. Resettlement Communities

Resettlement communities are those communities displaced by the Bui hydroelectric project. These seven communities are Bui, Bator/Akanyakrom, Dokokyina, Brewohodi, Lucene, Agbegikuro, and Dam Site. Brewohodi, Lucene, Agbegikuro, and Dam Site resettled first and they form resettlement part A (RPA) [16,29]. Bui, Bator/Akanyakrom, and Dokokyina resettled later and they form resettlement part B (RPB) [16,29]. The seven communities together form the Bui Power Authority (BPA) resettlement communities. In this study, the seven communities are the sample communities, out of the total affected communities used for analysis. Community sampling is to ensure that the findings represent the economic and social characteristics of those people most directly affected by Bui Hydroelectric project.

3. Materials and Methods

The flowchart (Figure 2) shows how sustainability assessment of the Bui dam was done. The method is a sequence of data collection, estimation of single preference index, estimation of index by criteria, and, finally, determination of the general sustainability index (a measure of sustainability assessment). The assessment process is shown in Figure 2 and described in detail in Sections 3.1 and 3.2 below.

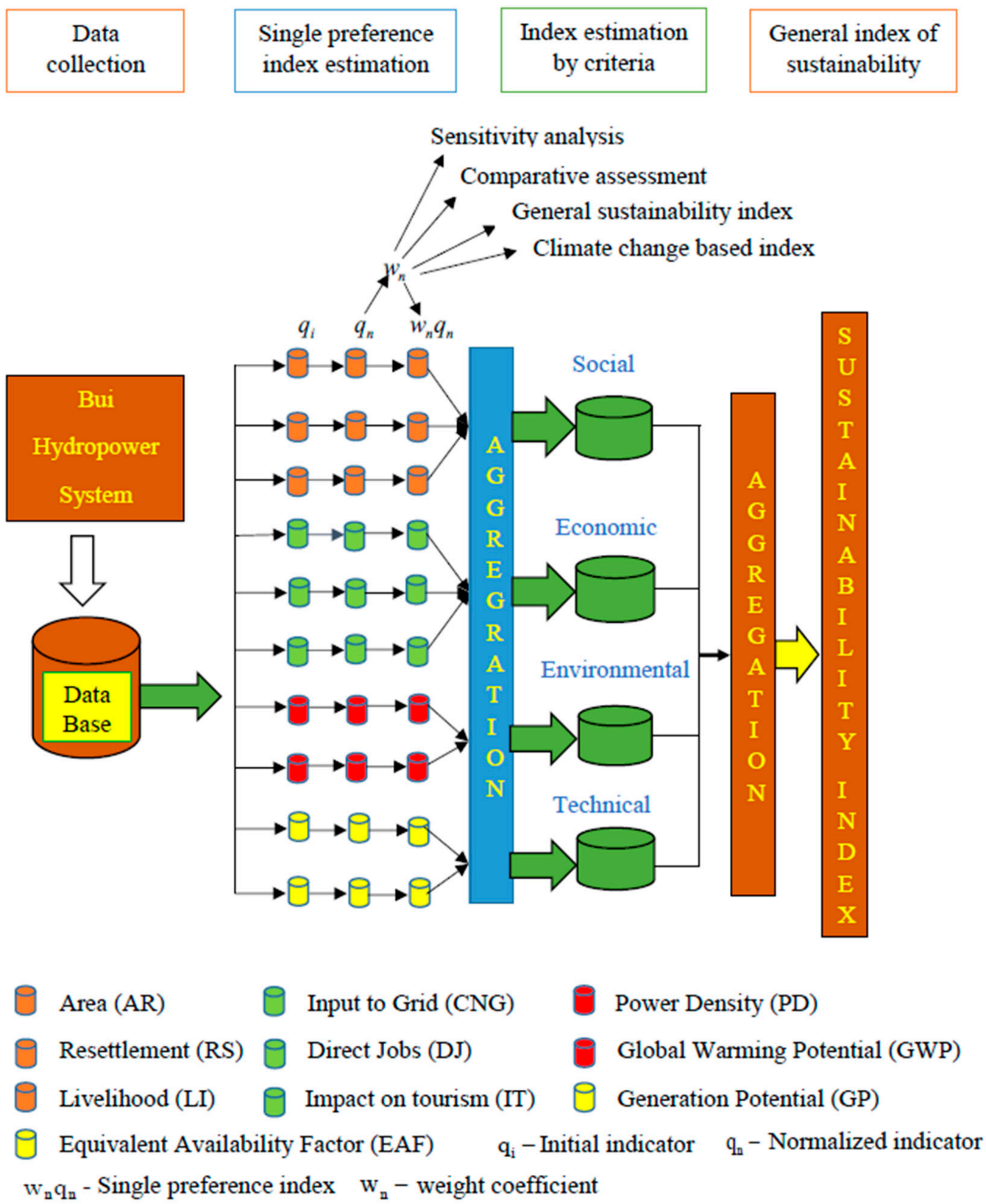

Figure 2. Graphical presentation of sustainability assessment procedure (adapted from [12]).

3.1. Data Collection

In this study, we employed both quantitative and qualitative data collection methods. Quantitative data including the dam's characteristics, environment, and production have been used to estimate most environmental and technical indicator values. Qualitative data were obtained via individual interviews and focus group discussions, and were used to estimate the socioeconomic impact of the dam on the resettlement communities. The total number of interviewees is 137:106 from RPB and 31 from RPA. Appendix B shows the number of interviewees, total number of households, and gender of interviewees. Male interviewees make up 65% of the total number of interviewees and female interviewees make up 35%. Interviewees' age is as follows: 6% under 20 years, 40% between 20 and 29, 39% between 30 and 39, 14% between 40 and 49, and 38% above 50 years. Also, four focus group discussions have been conducted in resettlements parts A and B, on resettlement issues. The number of people in a focus group was limited to 10 to 15, to promote easy handling of the group and to facilitate in-depth discussions. In RPB, focus group discussions were held for each community separately. In RPA, however, only one focus group discussion was held for all four communities because the communities are relatively small compared to RPB (Appendix B). During focus group discussions, men and women were put together as the issues for discussion are not gender-based. Key institutional actors who were interviewed for analysis include the resettlement officer of the Bui Power Authority and the assistant park manager of Bui National Park. Other key institutional actors in resettlement communities who were interviewed are chiefs, opinion leaders who represent communities in decision making process, and assembly man of RPB. After all qualitative data were collected, we found numeric estimates (indicator values) of data through an appropriate equation. The multi-criteria analysis tool was used to aggregate the indicator values to obtain an index (single preference index) showing an indicator's magnitude on a scale of 0 to 1. The procedure used to estimate the single preference index is described in Section 3.2.

3.2. Single Preference Index Estimation

The procedure for estimating the single preference index for a specific indicator (criterion) involves four steps:

1. Estimation of the indicator's initial value (q_i)
2. Estimation of its normalized value (q_n)
3. Estimation of its weight factor (w_n)
4. Estimation of its single preference index ($w_n q_n$)

Sections 3.2.1–3.2.4 explain how each of the four steps were carried out.

3.2.1. Initial Indicator Value (q_i)

Initial values for the following indicators were used for this study:

1. Area (AR)
2. Resettlement (RS)
3. Livelihood (LI)
4. Contribution to National Grid (CNG)
5. Direct Job (DJ)
6. Impact on Tourism (IT)
7. Power density (PD)
8. Global Warming Potential (GWP)
9. Generation Potential (GP)
10. Equivalent Availability factor (EAF)

The indicators cover the four pillars of sustainability assessment for energy systems: social, economic, environmental, and technical. We selected 10 indicators after a critical review of the literature on sustainability issues concerning the Bui dam. Major factors that influenced the selection are the availability of data and the purpose for building the Bui dam. The purpose of building the dam is to increase the generation capacity of Ghana and minimize power crises at the time. We started by selecting indicators that can measure the social implications of building the dam. We identified the resettlement communities as a suitable sample for investigating the social impact of the Bui dam on the local population. We noticed that livelihood and resettlement are the issues most discussed in the literature [16,18,20]. National and international environmentalists and human right activists opposed the dam project because of the potential negative environmental, health, and social impacts of the project on the local population [16,17]. They felt that the environmental and social impact assessment of the Bui dam underestimated the impacts on the local population. Our interactions with the resettlement communities show that the main occupations (fishing and farming) were negatively affected. We evaluated this negative impact by simply comparing the income levels of fishermen and farmers before and after resettlement, and used that to estimate the livelihood indicator (LI), which is under social criteria. With the resettlement indicator (RS), we evaluated how many of the resettlement promises have been delivered to resettlement communities. We allowed focus group discussions from resettlement communities to estimate, in percentage terms, to what extent the resettlement promises have been fulfilled. We gave the same privilege to the Bui Power Authority, which has been in charge of resettlement issues. Finally, the authors assessed and removed biases in the responses by using ground-based evidence of resettlement promises that have been delivered. Area indicator (AR) was used to evaluate how many square meters of land area were used to produce a kilowatt (kWh) of energy [30,31]. AR has the social implication of evaluating the value of land for power production, and can be used to ascertain whether it is worth using the area for power production. With economic criteria, we use indicators such as contribution to the national grid (CNG), Direct Job (DJ), and impact on tourism (IT) to assess the economic implications of Bui dam on sustainability. DJ has been used in instances to evaluate the economic implication of energy projects [32]. DJ is defined by the amount of direct labor required for a technology chain, averaged over total generation for the planned life of the plant [32]. A hydropower sustainability is assessed in either one of the four stages; early, preparation, implementation and operation stages [33]. In estimating DJ, we limited the analysis to the current workforce of the Bui dam because the assessment process is at the operating phase of the dam. We have, however, included the total workforce for planning and implementation stages as well for the purpose of other discussions. We used IT to assess the impact of building the dam on the main economic activity (tourism) the Bui dam area previously served. We needed to ascertain the implication of the Bui dam on tourism after 21% of the Bui National Park, which used to be a tourist site, has been inundated. We used the CNG indicator to evaluate the impact of Bui dam on the national grid. This indicator is very important because it assesses the main reason for constructing the Bui dam. One requirement of sustainability criteria is that they should be defined with indicators that measure quality corresponding to specific sustainability goals, and should also be based on timely information [1,13]. The sustainability goal of the Bui dam is that when it comes on board it should reduce the power crises at the time. Thus, the main reason for building the Bui dam is to add to the generation capacity of the country and minimize the power crises at the time. We intended to use the CNG indicator to ascertain the implications of the Bui dam in terms of improving access to electricity. The choice of CNG is therefore motivated by local knowledge of the energy situation of Ghana. For environmental indicators, we used the power density (PD) and global warming potential (GWP) as indicators to ascertain the environmental implication of the Bui dam. PD has been used as an indicator to assess the environmental impact of a hydropower dam [31,34]. We used PD to evaluate how much power the Bui dam is creating versus how much land area it has taken away. We used the PD value to evaluate whether Bui dam has taken more from the environment that it has given or vice versa. GWP estimates the amount of CO_2 emitted per Kilowatt hour of energy generated by the dam [35]. We used GWP to evaluate whether the Bui dam is a clean source or not. We have been motivated to use this indicator because clean energy is becoming a critical criterion for assessing renewable and sustainable energy systems [32]. With regard to the Bui dam, there seem to be disagreement about whether it is a clean source or not. The ESIA of Bui dam assumes that because of the small size of the reservoir compared to other large manmade lakes, its GWP will be insignificant. McCully [18] estimated that, based on the PD of the dam and the fact that it is a tropical reservoir, it is likely to be one of the worst emitters of greenhouse gases, with a high GWP. We used the GWP to verify which of these opinions is true, as well as capture the implications of Bui dam in terms of global warming. For technical criteria, we used the generation potential (GP) and equivalent factor (EAF). EAF has been used as a technical indicator to reflect the maximum possible generation available per year based on a unit's reliability [32]. We used EAF to capture the actual availability of the dam for power production (current generation). One of the key issues when defining a sustainability criterion is that it should reflect the longevity of systems design [1,13]. The Bui dam has been designed to have a long-term GP of 969 GWh/year. We use the GP to mimic the maximum impact possible in a typical year, where Bui dam can generate up to its maximum potential (future generation). Thus, in summary, AR, RS, and LI are social indicators; CNG, DJ, and IT are economic indicators; PD and GWP are environmental indicators; and GP and EAF are technical indicators. Each of the indicator values was obtained through an appropriate equation.

Area indicator was estimated in m^2/kWh using the equation:

$$\text{AR} = \frac{Reservoir_{coverage}(m^2)}{Energy_{generated}(kWh)} \tag{1}$$

As described above, the AR indicator evaluates the value of land for power production.

Resettlement indicator was estimated as a fraction (0 to 1) of the resettlement promises that were fulfilled using the equation:

$$\text{RS} = \frac{Reservoir_{coverage}}{Reservoir_{maximum\,coverage}} \times Average_{resind} \tag{2}$$

$Average_{resind}$ is the average resettlement indicator. The $Average_{resind}$ is used to estimate, on a scale of 0 to 1, whether the resettlement promises made by the Bui Power Authority (BPA) to the Bui resettlement communities (RPA and RPB) have been fulfilled. $Average_{resind}$ was estimated through focus group discussions in the resettlement communities to verify that those resettlement promises that were fulfilled. The resettlement officer of the BPA was also interviewed to verify the responses from the resettlement communities and to help eliminate biases. The resettlement promises comprises all packages of Bui Power Authority Resettlement Program [36]. The resettlement promises that have been assessed in this work are listed in Appendix D, together with the criteria for assessment in Appendix C. A summary of the results of the assessment sheet by RPA, RPB, Opinion leaders (OLs) of the two communities, a BPA resettlement officer, and the authors' assessment is shown in Appendix D. $Average_{resind}$ was calculated as an average value of all resettlement promises that were fulfilled. The ratio $Reservoir_{coverage}/Reservoir_{\text{maximum\_coverage}}$ was used to determine the value (relevance) of resettlement for different periods, so that the value of resettlement is not the same for all periods considered. In other words, when the reservoir has maximum coverage, it implies that the decision to resettle communities makes more sense than when the reservoir has minimum coverage. This ratio is a true observation in the field. People tend to settle in the reservoir along the river when the reservoir covers less area and move out of the reservoir when it covers a larger area. This ratio enables us to conduct the assessment on a seasonal basis.

We derived an equation that accurately predicted the Bui reservoir coverage area at a given time, using a relationship between the reservoir coverage area and water level in the dam (see [37]). The equation derived has an error of 0.03% and is given by:

$$Reservoir_{area} = 2.3981e^{0.0285x}, \tag{3}$$

where x is the water level in the dam. This equation is used to estimate the reservoir coverage in this paper.

Livelihood indicator was estimated using the equation

$$\text{LI} = 1 - \frac{Income_{present}}{Income_{past}}. \tag{4}$$

Livelihood sources for resettlement communities before resettlement were fishing and farming. Average income levels of fishermen and farmers before and after resettlement were used to estimate the livelihood indicator (Equation (4)). $Income_{present}$ represents the average income of fishermen and farmers in the resettlement communities after resettlement. $Income_{past}$ represents the income levels of the fishermen and farmers in the communities before resettlement. The ratio $Income_{present}/Income_{past}$ represents the fraction of the past income (before resettlement) that farmers and fishermen of the resettlement communities still enjoy at the time of the assessment (after resettlement). The value of 1 in Equation (4) represents an ideal condition where the farmers and fishermen of the resettlement communities enjoy the maximum income. During focus group discussions, farmers and fishermen identified that their income levels before resettlement were ideal and so a value of 1 was given to serve as a reference. Equation (4) therefore represents the fraction of income lost by farmers and fishermen in the resettlement communities due to the construction of the Bui dam. Thus Equation (4) was used to estimate the impact on the livelihood of resettlement communities due to construction of the Bui dam.

The contribution to national grid indicator was used to estimate the energy Bui dam contributes into the national grid as a percentage of the total energy generated from all sources. CNG indicator was estimated using the equation

$$\%\ CNG_{Bui} = \frac{CNG_{Bui}}{CNG_{Total}} \times 100\%. \tag{5}$$

CNG indicator was used to measure the impact of Bui dam generation on the entire grid. Information on Bui's projected power supply was obtained from an electricity supply plan [38,39].

The direct job indicator was used to estimate the number of jobs that Bui dam has directly created. DJ estimated in persons-month/GWh, was used to estimate on average the number of persons that Bui dam employs in generating a GW of electricity. DJ was estimated using the equation

$$\text{DJ} = \frac{Number\ of\ direct\ employees \times \frac{1}{12} month/year}{Energy\ generated}. \tag{6}$$

This indicator is used to measure the economic impact of the Bui dam [32] at the operational phase of the dam. Information on the number of employees Bui dam was estimated through interviews with a resettlement officer from the Bui Power Authority.

The impact on tourism indicator was used to evaluate the impact on tourism of the Bui National Park, of which 21% is now covered by the reservoir. IT was estimated using the equation

$$\text{IT} = \frac{Number\ of\ visitors\ recorded\ post - inundation\ era}{Number\ of\ visitors\ recorded\ pre - inundation\ era}. \tag{7}$$

The IT indicator evaluates what tourism is like now (post-inundation) compared to before (pre-inundation). This indicator estimates the fractional available tourism potential of the Bui National Park at the time of the assessment. IT measures the economic value of how tourism has been affected due to the construction of Bui dam. Information on the number of tourists who visited Bui National Park was obtained from the management of Bui National Park.

The power density indicator, also known as the environmental index, measures the environmental impact of a hydroelectric dam [31,34]. PD for Bui dam was estimated using the equation

$$\text{PD} = \frac{Installed\ capacity\ (W)}{Reservoir_{coverage}(m^2)} \tag{8}$$

The GWP indicator was estimated in $kgCO_2$-eq/kWh using the IPCC methodology for estimating land converted permanently to flooded land [35]. Details of this method may be found in [35].

The long-term generation potential of the Bui dam is 969 GWh/year [15]. GP was used to model the impact of Bui dam under a condition where it is able to generate up to its maximum potential. GP for a specific period was estimated using the equation

$$GP_{period} = \frac{energy\ generated_{period}}{totalenergy\ generated_{year}} \times 969GWh/year. \tag{9}$$

GP was estimated on a monthly basis (GWh/month) and used as a key determinant of sustainability to model the long-term generation potential of the Bui dam.

The equivalent availability factor indicator evaluates the availability of an energy system for power production, taking into account the reliability of generation units [32]. Bui dam was designed as a peaking plant to produce power at the peak hours of the day. The EAF for a specific period of the Bui dam was estimated using the equation

$$EAF_{period} = \frac{energy\ generated_{period}\ (MWh)}{peak\ capacity(MW)\ \times\ time(\frac{h}{period})} \tag{10}$$

EAF was used as a key determinant of sustainability to assess the actual availability of the Bui dam for power production.

All the above indicators were estimated on a monthly basis and their average seasonal values calculated. Table 1 shows the seasonal average values of the 10 indicators used for this study.

Table 1. Initial indicator values.

m	Initial Indicator Values (q_i)-k									
SEASON	**AR**	**RS**	**LI**	**CNG**	**DJ**	**IT**	**PD**	**GWP**	**GP**	**EAF**
JFM	6.8800	0.6340	0.9930	4.1670	0.2320	0.9700	1.1560	2.2230	68.7130	0.6000
AMJ	6.4000	0.5970	0.9280	4.1940	0.2290	0.0680	1.2270	2.0940	69.4290	0.5940
JAS	5.8680	0.5680	0.9140	4.5590	0.2210	0.1030	1.2970	1.9900	74.4860	0.4790
OND	4.6350	0.6880	0.9250	6.3300	0.1440	1.6840	1.0660	2.4110	110.3720	0.7660

Notes: Table 1—m × k matrix of m seasons and k initial indicators; JFM—dry season ; AMJ—pre-wet season, JAS—wet-season; OND—post-wet season; AR—Area indicator (m^2/kWh); RS—Resettlement indicator (fraction); LI—Livelihood indicator (fraction); CNG—Contribution to National Grid indicator (%); DJ—Direct job indicator (person-months/GWh); IT—Impact on tourism indicator (fraction); PD—Power density indicator (W/m^2); GWP—Global Warming Potential indicator ($kgCO_2$-eq/kWh); GP—Generation potential indicator (GWh/mon); EAF—Equivalent availability factor indicator (fraction).

The indicators in Table 1 have been estimated in different units. In order to evaluate the equivalence, they are brought to a common scale through normalization. By normalization, a direct comparison is achieved because each indicator is dimensionless (no units), with values between 0 and 1.

3.2.2. Normalized Indicator Values (q_n)

Normalization is achieved through mathematical expressions that use a membership function $q_i(X_i)$ for each indicator X_i [40,41]. For each indicator X_i we select the maximum, $max(X_i)$, and minimum, $min(X_i)$, and evaluate whether the function $q(X_i)$ increases or decreases with the increased value of X_i. If the membership function *q(X*$_i$*)* increases with indicator X_i, their relationship is expressed by:

$$q_i = q_i(x_i) = \begin{cases} 0 & if\ x_i \leq MIN_i, \\ \frac{x_i - MIN_i}{MAX_i - MIN_i} & if\ MIN_i < x_i \leq MAX_i \\ 1 & if\ x_i > MAX_i; \end{cases} , \quad (11)$$

If membership function $q(X_i)$ decreases with indicator X_i, their relationship is expressed by:

$$q_i = q_i(x_i) = \begin{cases} 1 & if\ x_i \leq MIN_i, \\ \frac{MAX_i - x_i}{MAX_i - MIN_i} & if\ MIN_i < x_i \leq MAX_i, \\ 0 & if\ x_i > MAX_i. \end{cases} \quad (12)$$

Each indicator was examined to see if it has a positive or negative impact on sustainability. If an indicator value increases sustainability (positive impact), the increasing membership function is applied to that indicator and vice versa. For example, as CNG increases, sustainability increases and so the increasing membership function (Equation (11)) is applied to CNG. On the other hand, as LI increases, sustainability decreases and so the decreasing membership function (Equation (12)) is applied to LI. Each indicator was normalized within the intervals plus/minus 3 standard deviations from the mean value estimation. The primary reason is to eliminate edge conditions 0 and 1 in the membership function and conserve all data values [42]. Another reason is to set 0.5 as the mean sustainability index, differentiating sustainable indices (>0.5) from unsustainable indices (<0.5). Finally, normalizing in this way makes the comparison meaningful and also takes notes of how Bui dam is designed to produce power (as a peaking plant). Bui dam produces an equivalent amount of energy each day. It is an Independent Power Producer (IPP), designed to produce power on demand and at peak hours of the day. Table 2 shows the normalized indicator values obtained after an appropriate membership function is applied to each indicator value in Table 1.

Table 2. Normalized indicator values (q_n).

m	Normalized Indicator Values (q_n)-k									
	Social		Economic			Environmental			Technical	
SEASON	**AR**	**RS**	**LI**	**CNG**	**DJ**	**IT**	**PD**	**GWP**	**GP**	**EAF**
JFM	0.3140	0.5455	0.3085	0.3791	0.3829	0.4343	0.4406	0.4538	0.3837	0.4841
AMJ	0.4096	0.4080	0.4282	0.3841	0.3967	0.6587	0.5789	0.5907	0.3906	0.4743
JAS	0.5155	0.3002	0.7633	0.4525	0.4334	0.6500	0.7152	0.7011	0.4395	0.2870
OND	0.7610	0.7463	0.5000	0.7843	0.7869	0.2569	0.2653	0.2544	0.7863	0.7546

Notes: Table 2—m × k matrix of m seasons and k normalized indicators.

After normalization, weighting information about each indicator must be applied to evaluate the importance of each indicator under a particular condition or case study.

3.2.3. Weight Coefficient Estimations (w_n)

A decision support system interface (DSS APIS) [41], which is a modification of certified DSS ASPID-3W [43], was used to generate a weight coefficient for indicators based on non-numeric weighting information. APIS was used because of its ability to estimate weight using non-numeric, non-exact, and non-complete (NNN) information [41,43]. This approach is extremely important because most of the information obtained about the weight of indicators are not numeric but their magnitude and impacts can be described. With APIS's capability to model NNN information, it makes it possible to assign weights to indicators in descriptive language. This is done in APIS by the use of a comparative proposition between the indicators. Thus, a < or > or = b, is used to specify which indicator(s) are weightier compared to other indicator(s). APIS then generates a numeric estimate for weight according to the information given about the weights. In this paper four different cases are considered. In each case, weighting information is input by the authors and APIS generates the numeric estimates of the input weighting information.

Case 1: Sensitivity Analysis of Indicators

In this case, priority is given to one indicator at a time, with the other indicators having equal preference. For example, we prioritize AR with the non-numeric weighting information:

$$AR > RS = LI = CNG = DJ = IT = PD = GWP = GP = EAF. \tag{13}$$

APIS is then employed to generate a numeric estimate of the weighting information in Equation (13) and also to calculate the General Sustainability Indices (GSI). The process was repeated for each indicator.

Case 2: Multi-Criteria Analysis of Sustainability Indicators: Comparative Assessment of Sustainability Indicators

This case takes into account how indicators were prioritized during Bui dam planning and implementation. The information was obtained through an extensive literature review to obtain details on decision-makers' interest in planning and implementing the Bui dam project. This information is summarized in the introduction. Weighting coefficient estimate was derived using the decision-makers, priority as summarized below:

$$GP \approx CNG \approx DJ > EAF \approx RS > LI > IT \approx PD > GWP \approx AR. \tag{14}$$

The percentage contribution of each indicator and criteria was estimated using the weight coefficient and normalized indicator values. The percentages were used to determine the priority given to social, economic, environmental, and technical criteria during the Bui dam project development.

Case 3: Use of Normalized Mean (Single Preference Index) Values to Derive Weight

In this case, normalized mean values of indicators are used as the basis to estimate the weight coefficient. The normalized value of an indicator gives an idea of the natural weight of that indicator in comparison to other indicators on a common scale. This case is used to model the consequences of decisions taken in case 2. The non-numeric equation used to estimate weight coefficient is according to Figure 3 and expressed as:

$$\begin{gathered} w(GWP) \approx w(PD) \approx w(EAF) > w(RS) \approx w(LI) \approx w(AR) \approx w(IT) > w(CNG) \approx w(GP) \approx w(DJ) \\ Q(JFM) < Q(AMJ) < Q(JAS) < Q(OND). \end{gathered} \tag{15}$$

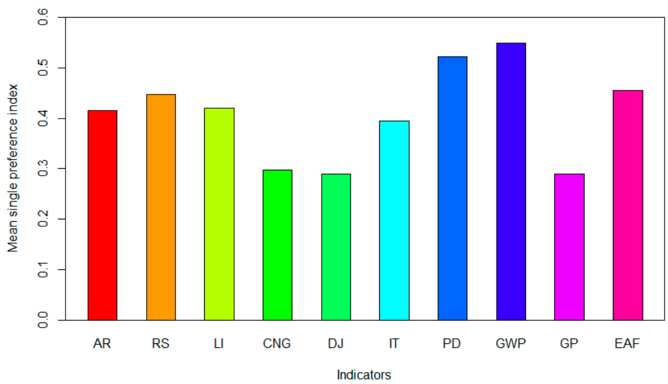

Figure 3. Mean single preference index of indicators.

The second part of Equation (15) is used to impose the preference in season determined from the data.

Case 4: Climate Change-Based Index

In this case a climate change index is built for the Bui dam based on predicted seasonal climate change impacts on the Black Volta River and the Bui dam. The predictions used were those discussed as consequences of neglecting climate change impacts on the Bui dam at the Ghana dams forum [19]. Table 3 summarizes the seasonal climate change impacts predicted and the corresponding seasonal non-numeric equation used.

Table 3. Seasonal climate change prediction and corresponding non-numeric equation.

Seasonal Climate Change Prediction	Non-Numeric Weighting Information
Decreasing rainfall in the month of April	$w(AMJ) < w(JFM)$
Increasing duration of the dry season	$w(AMJ) < w(JFM)$
Increasing unpredictability of the onset of the rainy season	$w(AMJ) < w(JFM)$
Increase and intensification of rainfall at the end of the rainy season	$w(JAS) < w(OND)$
Slight decrease of river flow	$w(GP) > w(EAF)$
Increase in flood-events	No non-numeric input information

Notes: w—weight; w(AMJ)—weight of AMJ; w(GP)—weight of generation potential, etc.

The predictions are summarized into the non-numeric equation

$$w(AMJ) < w(JFM) < w(JAS) < w(OND),\ w(GP) > w(EAF). \tag{16}$$

3.2.4. Single Preference Index Estimations ($w_n q_n$)

The sustainability index of a specific criterion (indicator) q_n, having a weight factor w_n is determined using

$$q_n(q_n; w_n) = w_n q_n. \tag{17}$$

Equation (17) is the single preference index of a specific indicator. We estimate the sustainability index of a specific criteria Q_n, having n number of q_n criterion (indicators), each with a weight factor w_n, by the additive aggregation all indicators under that criterion:

$$Q_n = \sum_{n=1}^{n=k} w_n q_n. \tag{18}$$

In this paper, social criteria have three indicators and so $n = 3$. Economic criteria have $n = 3$ indicators. Environmental criteria have $n = 2$ indicators and technical criteria have $n = 2$ indicators (Table 2).

The General Sustainability Index (GSI) Q, is given by the sum of all criterion (indicators) q_n, multiplied by their relative weight w_n. Thus,

$$Q = \sum_{n=1}^{n=k} w_n q_n. \tag{19}$$

In this paper, 10 indicators were used and so . All results obtained in this work are quality assessments and are presented as sustainability indices.

4. Results and Discussion

4.1. Case 1: Sensitivity Analysis of Sustainability Index

A sensitivity analysis shows that most GSI (Figures 4–7) values are lowest in the JFM season and highest in the OND season. Thus, Bui dam's quality is highest in the OND season and lowest in the

JFM season. The index formed is highest (0.7312) when DJ is prioritized and least when LI is prioritized (0.3525). Thus, per the estimations of this work, Bui dam's contribution to sustainability (sustainable development) is mainly in terms of providing jobs for the immediate workforce. In its operational phase, the immediate workforce for the Bui dam is estimated from interviews to be 140 people. It is also worth mentioning that, during the construction phases, the Bui dam project employed close to 6000 Ghanaian artisans/laborers and close to 300 Chinese and 80 Parkistani contractors as expatriate staff on site [44]. Even though the Bui dam employed 140 people at its operational stage, the dam has contributed least to improving the livelihood of the affected communities, as can be seen from the GSI value of 0.3525. Interviews with local population reveal that very few locals are employed at the dam site. They added that, even when they are employed, they only occupy lower ranks because the Bui Power Authority requires special skills and expertise, which they lack. Focus group discussions with resettlement communities also reveal average losses in the income levels of fishermen and farmers of up to 90% due to resettlement. Dam projects in general have been noted for their negative environmental and social impacts and have hardly improved the livelihood of the affected communities [16]. Obour et al. [16] stated that not much has been done to improve the livelihood of the BPA resettlement communities. These findings about the livelihood of the resettlement communities is still valid, even at the time that this work was carried out. So, the contribution of the Bui dam project to improving the livelihood of resettlement communities is something we look forward to.

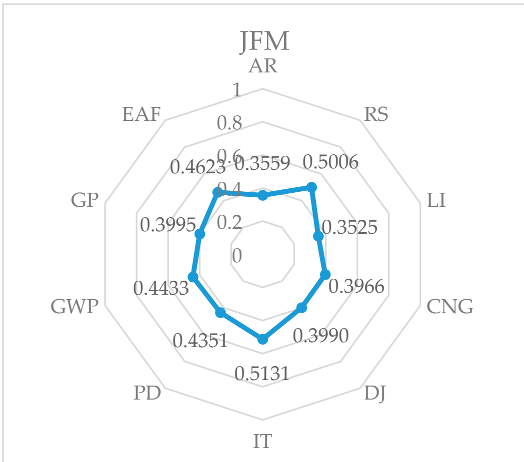

Figure 4. General sustainability index values (JFM).

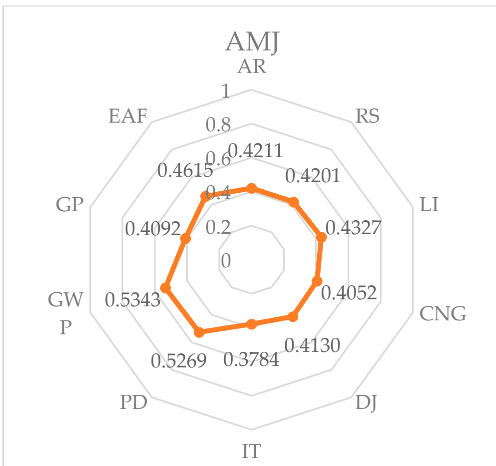

Figure 5. General sustainability index values (AMJ).

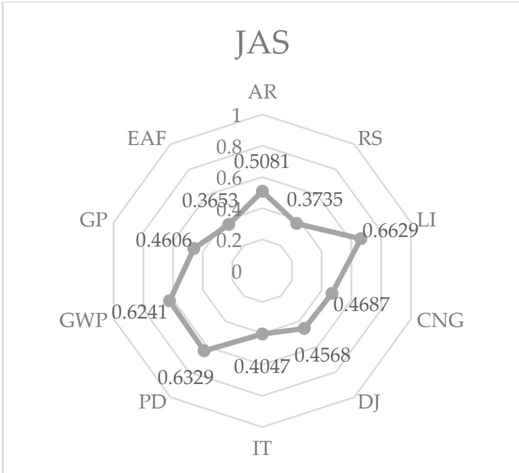

Figure 6. General sustainability index values (JAS).

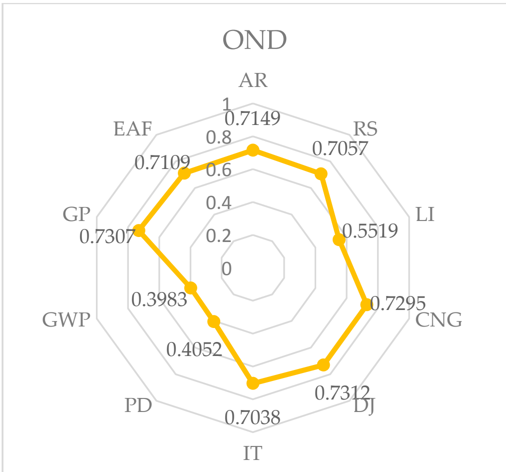

Figure 7. General sustainability index values (OND).

4.2. Case 2: Multi-Criteria Analysis of the Bui Dam Project Development

Multi-criteria analysis of the Bui hydroelectric project reveals the relative weight of indicators used (Table 4). Table 5 shows the percentage contribution of these indicators based on their weights (Table 4) and normalized values (Table 2) using an additive aggregation function (Equation (18)).

Table 4. Weight coefficient estimations (Case 2).

	Social			Economic			Environmental		Technical	
	AR	**RS**	**LI**	**CNG**	**DJ**	**IT**	**PD**	**GWP**	**GP**	**EAF**
w_n	0.0063	0.1250	0.0813	0.1937	0.1937	0.0375	0.0375	0.0063	0.1937	0.1250

Table 5. Percentage contribution by criteria to general sustainability index (quality).

SEASON	Social	Economic	Environmental	Technical
JFM	22.77	40.36	4.63	32.24
AMJ	21.41	39.74	6.16	32.69
JAS	23.38	7.10	7.10	27.51
OND	19.03	1.58	1.58	33.83
Average (with bias)	21.65	41.92	4.87	31.57
Average (without bias)	18.04	34.93	6.09	39.46

The results show that in planning and implementing the Bui dam about 76% priority was given to technical and economic aspects. Social and environmental aspects have the least priority (Table 5 and Figure 8). This is mostly the practice for planning and implementing most energy projects. For Bui dam, we estimated the priority considering that there are three social, three economic, two environmental, and two technical indicators. Recognizing that there could be a possibility of bias in the results because of the different number of indicators, we estimate firstly the priority of each criteria without considering the number of indicators. Secondly, we eliminate the bias by assuming that the criteria (social, economic, environmental, and technical) should contribute equally (25%). The reason for the assumption is to allow the weighted and normalized values of the indicators to control the priority estimated, instead of the number of indicators within specific criteria. We justify this assumption by the fact that, in the sustainability concept, all pillars are of equal importance (social, economic, environmental, and technical). The results for each case (Table 5) show that the weight of indicators (Table 4) and the normalized value of indicator used control the priority rather than the number of indicators. When bias was not eliminated, we obtained 21.65%, 41.92%, 4.87%, and 31.57%, respectively for social, economic, environmental, and technical criteria. When bias was eliminated, we obtained 18.04%, 34.93%, 6.09%, and 39.46%, respectively. Even though technical criteria have two indicators, they have the highest percentage priority (39.46%) due to high normalized indicator values and weighting information. There are three indicators in social criteria but it has a relatively lower percentage priority (18.04%). So, ultimately, the weight of indicators and indicators' normalized values determine the percentage priority and not necessarily the number of indicators in specific criteria.

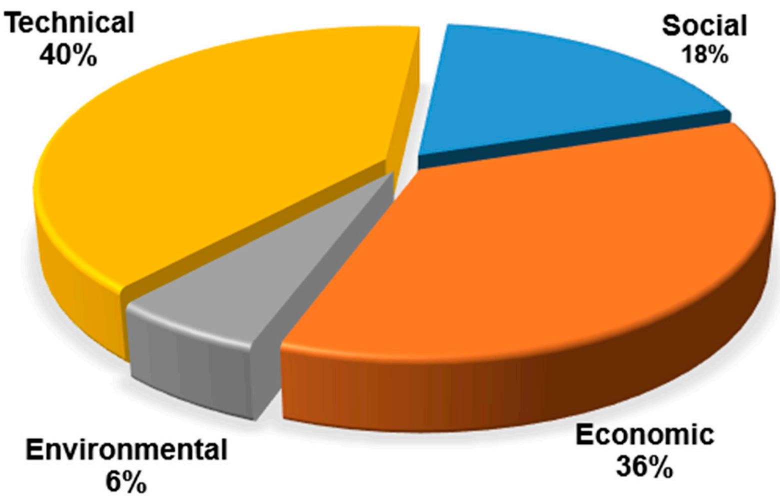

Figure 8. Decision makers' priority for planning and implementing Bui dam.

Interactions with resettlement communities also reveal that they are displeased about issues of resettlement and their livelihood. Eighty-four percent of total interviewees liked the Bui dam project before its planning and implementation stages but only 51% of total interviewees liked the Bui dam after its construction. Interviewees explained that the Bui dam has put them in crisis. Obour et al. [16], reported that people in the resettlement communities were not satisfied with the location of their new homes and felt the dam had impoverished them. According to Obour et al. [16], a household head said:

> *I would have preferred being relocated into a squatter house close to the river to enable me to have easy access to the river than living in plush houses located far away from the river.*

An analysis of questionnaire responses revealed that just about 62% of resettlement promises have been fulfilled at the time of assessment (Appendix A). In general, interviewees from the resettlement communities expressed great displeasure about their resettlement. The assembly man of resettlement part B said:

To me, livelihood constitutes 80% of resettlement. If you bring people to a place and they have lost their livelihood, what good have you done them? I think the beauty of resettlement blindfolds people who visit the resettlement communities from seeing the realities on the ground.

Obour et al. [16], also reported that farmland flooded by the river is as follows: 34% (<4 ha), 40% (between 4 and 10 ha), 10% (>10 ha), and 16% (do not remember actual size). After resettlement, each farmer got 0.8 ha. The situation reveals that a farmer with farmland of less than 4 ha (~3 ha) now has 0.8/3 = 26.7%). This implies that farmers with the smallest land area have lost 73.3% of their farmland area. If we translate this directly into income, it will imply that farmers of the resettlement communities have lost up to 73.3% of their income level according to [16]. During focus group discussions, we estimated up to 83.3% of income lost for farmers and even higher for fishermen. Fishermen at Bator/Akanyakrom said that they have been resettled several kilometers from the new lake, which makes access to the lake difficult. Urban et al. [21] report is similar. Fishermen also reported two main challenges. Firstly, fishermen raised issues of competition in fishing between resident river fishermen and immigrant lake fishermen. According to resident fishermen, immigrant fishermen have equipment for fishing in the lake and are also more experienced at fishing in the lake. Fishermen also said the dangerous nature of the lake makes it difficult for inexperienced resident fishermen. Fishermen report that four fishermen have drowned in the lake because of inexperience. Urban et al. [21] also reported the death records and stated that it is more dangerous to fish in the current lake conditions. Secondly, fishermen said studies have shown that the size of the lake can support just 100 fishing canoes. The fishermen said the presence of immigrant fishermen from all over West Africa has heightened competition for fishing within the reservoir. Among the criteria used in this paper, social issues of livelihood are major concerns for resettlement communities. During data collection, we noticed that only the first phase of the livelihood improvement program has been carried out. We confirmed this fact with the resettlement officer of the Bui Power Authority.

4.3. Case 3: General Sustainability Index (GSI) of the Bui Dam

The weight coefficient estimate used to determine GSI is shown in Figure 9. The GSI of the Bui hydroelectric project shows Bui dam's quality on a scale of 0 to 1 (Figure 10). Numeric estimate of GSI in Figure 10 is shown in Table 6. The prefix SI in Figure 9 indicates social indicator. Thus SI-AR indicates that Area is a social indicator. Similarly, EvI, TI, EcI indicates environmental, technical and economic indicators respectively, and they show the criteria to which the indicators attached to them belongs to. The blue lines show the probability of dominance, on a scale of 0 to 1, of one estimation over another. The red marks on either side of the actual estimation (middle mark) show the -1 and $+1$ standard deviations. The mean value (actual estimation) is shown in the middle of the red marks.

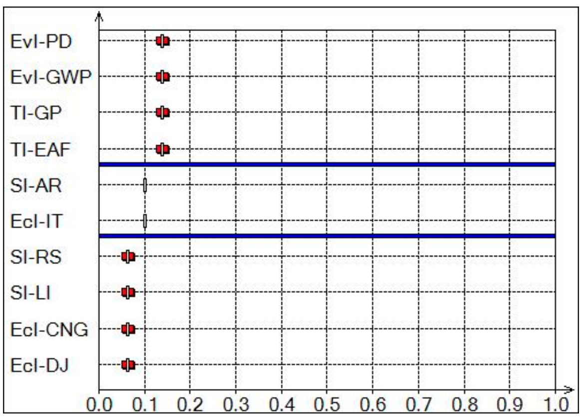

Figure 9. Weight coefficient estimation (Case 3). SI-Social indicator; EcI-Economic indicator; EvI-Environmental indicator; TI-Technical indicator.

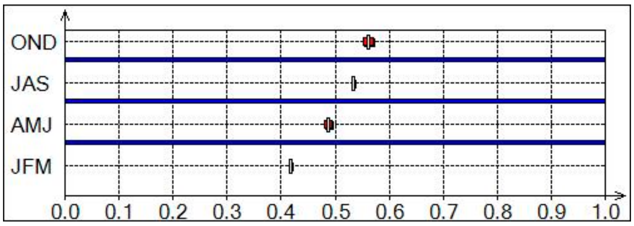

Figure 10. General sustainability index estimations (Case 3).

Table 6. Numeric estimate of general sustainability index (Case 3).

Season	Min.	Max.	Sustainability Index	Standard Deviation
JFM	0.4337	0.4494	0.4415	0.0064
AMJ	0.4487	0.4657	0.4572	0.0069
JAS	0.5068	0.5288	0.5178	0.0090
OND	0.5561	0.6108	0.5835	0.0223

From Table 6, the sustainability index of the Bui hydropower project lies approximately within the range 0.4 to 0.6. The pre-wet (AMJ) season and dry (JFM) season are below the mean sustainability index mark (0.5). The wet (JAS) season is just above the mean sustainability index mark. The post-wet (OND) season has the highest sustainability index mark (>0.5). Per the estimation of this work, the Bui dam is most sustainable in JAS and OND seasons and least sustainable in JFM and AMJ seasons. In general, the Bui hydroelectric project has a mean sustainability index less than 0.6. This index is a measure of the quality of the Bui hydroelectric project. More importantly, it reflects how the decisions taken in the planning and implementation of the dam have impacted the dam's quality. The results show that giving more attention to the technical and economic aspects of energy projects does not make for sustainable energy projects. This is obvious in the average sustainability index of 0.4–0.6. With Bui dam, ESIA appears to have been merely a bureaucratic requirement rather than an actual commitment to sustainability. The findings of the ESIA show underestimations or inadequate treatment of social and environmental issues. The Global Warming Potential, for instance, has been neglected on the basis that the reservoir coverage area is small compared to other large man-made lakes in the world. We estimated the net average Global Warming Potential of the Bui dam to be 2.179 $kgCO_2$-eq/kWh, which could reach 2.350 $kgCO_2$-eq/kWh. According to [45], the greenhouse gas (GHG) emission rate of a tropical reservoir ranges from 1.3–3.0 $kgCO_2$-eq/kWh. The emission rates of the Bui dam from our estimation fall within this range. McCully [18], was right when he said Bui dam's GWP could be compared to three well-studied Brazilian dams, whose emission are about 2.154 $kgCO_2$-eq/kWh. McCully's [18] assertion on the greenhouse gas emissions was based on the location of the Bui dam (tropical reservoir) and the power density of the Bui dam (0.91 W/m^2), which is comparable to the power density of the three well-studied Brazilian dams (0.90 W/m^2), which are also located in the tropics. The PD or environmental index measures the environmental impacts of a dam. As a ratio of installed capacity to area flooded, the value of 0.91 W/m^2 is small, suggesting a high impact. Thus, the power Bui dam is bringing is comparable to the land area it is flooding. The high GWP of the Bui dam also raises questions as to how clean the dam is. In summary, the PD and GWP values estimated for the Bui dam raise concerns about the environmental impact and cleanliness of the Bui dam, key issues in the sustainability discourse. A pertinent question worth considering is whether large hydroelectric dams can be considered as renewable energy and clean energy sources. The PD and GWP values of the Bui dam prove contrary to expectations of a sustainable and clean hydropower project. Our survey on the social impacts of the dam proves that Bui dam has significant negative impacts on livelihoods in resettlement communities. It is our view that indices may be improved by giving attention to environmental and social issues, since they are aspects that can be managed through appropriate environmental and social management planning.

4.4. Case 4: Climate Change-Based Index (CCI)

The weight coefficient estimate used to determine GSI is shown in Figure 11. The climate change-based index of the Bui hydroelectric project (Figure 12) shows how the GSI of the Bui dam will change with predicted climate change impacts. Numeric estimate of GSI in Figure 12 is shown in Table 7.

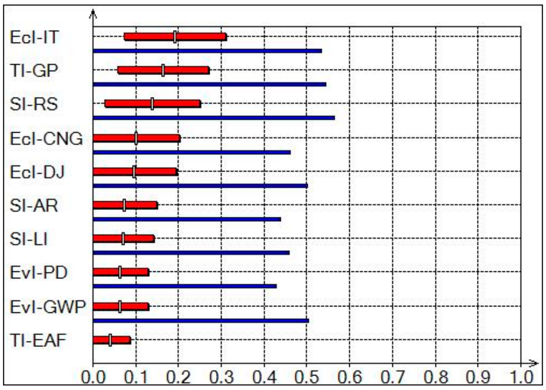

Figure 11. Weight coefficient estimations (Case 4).

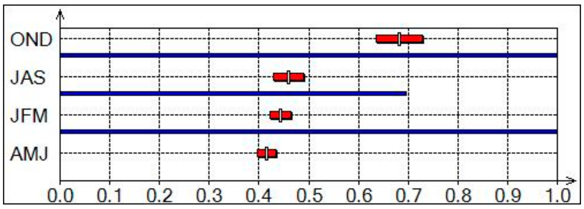

Figure 12. General sustainability index estimations (Case 4).

Table 7. Numeric estimate of general sustainability index (Case 4).

Season	Min.	Max.	Sustainability Index	Standard Deviation
JFM	0.3839	0.5611	0.4423	0.0205
AMJ	0.3425	0.4941	0.4155	0.0168
JAS	0.3485	0.5991	0.4597	0.0290
OND	0.5125	0.7845	0.6826	0.0451

The results (Table 7) indicate that under the impact of predicted climate change, the Bui dam will be sustainable (>0.5) only in the OND season. The Bui dam will be least sustainable (<0.5) in the JFM, AMJ, and JAS seasons. The fact that climate change studies were not incorporated into the Bui dam design [19,20] raises concerns about Bui dam's ability to cope with climate change impacts. The results obtained from this work indicate that if the predicted climate change impacts on the Black Volta and the Bui dam occur, the Bui dam will be highly susceptible to the impact of seasonal climate change, specifically in the JFM, AMJ, and JAS seasons. This is contrary to what the environmental and social impact assessment of the Bui dam suggested before its construction. The ESIA of the Bui dam stated that a changing climate in turn will have major implications for the safety and performance of dams, but this will only happen over a very long term (i.e., thousands of years). McCully [18], disagrees with the second part of the statement "but this will only happen over the very long term (i.e., thousands of years)". According to his explanation, the ESIA implied that the impact of climate change on the dam safety does not need to be considered as the dam designers have allowed for the "possible maximum flood" (PMF) event. McCully [18] stated that though that is standard practice in dam design, it is based on a statistical analysis of the PMF, which is based on historical hydrological data that does not reflect climate change. In McCully's [18] view, PMF needs to be calculated taking into account potential future hydrologies. Wolfram et al. [19] also pointed out that it is a serious oversight that the impact of global climate change was not considered when plans for constructing the Bui dam were evaluated and finalized. The results of this work show that, due to neglect of the potential seasonal climate change impact when designing the Bui dam, the dam is susceptible to the impact of seasonal climate change. The dam will be affected in the dry season (JFM), the pre-wet season (AMJ), and the post-wet season (OND).

5. Conclusions

This paper assesses the sustainability (quality) of the Bui hydropower system in Ghana, in its operational phase, using selected indicators and a multi-criteria analysis tool, APIS (ASPID-3W). The findings of this study are summarized below:

1. In general, the weight of indicators used for sustainability assessment of the Bui dam is in the decreasing order $GWP > PD > EAF > RS > LI > AR > IT > CNG > DJ > GP$. In terms of criteria, they have the order environmental > social > technical > economic. Thus, in the operational phase of the Bui dam, environmental and social issues are strong determinants of sustainability, while technical and economic issues are weak determinants of sustainability. During focus group discussions in resettlement communities, we estimated an average loss of fishermen's and farmers' income of up to 90% based on the data collected. Farmers claim to have lost up to 83.3% and fishermen over 90%. The farmers explain that the size of land given to them after resettlement is small compared to what they had before. Farmers explain further that the land given to them is infertile and so their harvests are minimal. Fishermen indicate that they have been resettled far from the river and access to the river is a major difficulty. Fishermen further explained that they face competition with immigrant fishermen who fish in the lake. Resident fishermen are disadvantaged because they lack the skills and equipment required to fish in the lake. We also explored the percentage of resettlement promises that were met at the time of the assessment. We estimated, based on objective evidence, that an average of 62% of resettlement promises have been fulfilled. Information gathered from resettlement part A, resettlement part B, Opinion Leader 1, Opinion Leader 2, and Bui Power Authority Resettlement officer are 50%, 52%, 58%, 49%, and 76% fulfilled promises, respectively. A general concern is that only the first phase of the livelihood improvement program, which is part of the strategy to improve and diversify livelihood in the resettlement communities, has been carried out. Per our estimation, the livelihood improvement program is a major step in helping resettled people adapt to difficulties in their new environment. The method used is a multi-criteria analysis and the approach is suitable to be applied for all energy options as a pre-feasibility analysis tool or actual assessment tool. It has been used to perform a quality assessment (sustainability assessment) of single energy projects or to evaluate and select the most sustainable energy option from a list of energy options. In either case a critical factor is to clearly define the options for the assessment.
2. The priority of indicators for developing the Bui dam was in the decreasing order $GP \approx CNG \approx DJ > EAF \approx RS > LI > IT \approx PD > GWP \approx AR$. In terms of criteria, the order was technical > economic > social > environmental. The results show that Bui dam was validated in reverse manner to the actual weight of the indicators used. This shows more emphasis on the techno-economic validation of the energy project, which does not reflect a fair sustainability concept. Our findings indicate that issues of the environment such as power density (environmental index), which measures the environmental impact, were not properly considered during the planning and implementation of the Bui dam. The dam is also estimated to emit a net average 2.179 $kgCO_2$-eq/kWh with the possibility of reaching 2.350 $kgCO_2$-eq/kWh, indicating that the Bui dam has a high global warming potential. In our estimation, it is better to use the PD as a measure of the impact of a hydroelectric dam rather than indicators such as GP, the CNG,

and rated capacity. During construction of the Bui dam, the government of Ghana, driven by the energy crises at the time, was only concerned with adding to the generation capacity of the country to minimize the power crises. This has led to a neglect of very important social and environmental issues. The method used in this paper is a quantitative measure of sustainability of a hydropower project on seasonal scale (JFM, AMJ, JAS, and OND). This method is new and is possible to carry out on any hydropower plant across the world with a suitable choice of indicators. Our recommendation, however, is that indicator selection needs to be improved upon to capture all the necessary information regarding the sustainability issues of the hydropower plant under consideration.

3. The quality (sustainability index) of the Bui dam in Ghana ranges from 0.4 to 0.6. The dam is unsustainable (<0.5) for the JFM and AMJ seasons but sustainable (>0.5) for JAS and OND. JAS and OND seasons have indices below 0.6. Thus, on the whole, the Bui hydroelectric project has an average but weak sustainability index. The quality assessment of the Bui dam, as revealed by this study, is an average mark. This index value takes into account major issues of concern to international and local social and environmental activists during the planning and implementation of the dam and should be interpreted in that regard. That is, the index assesses the quality of the total process of planning and implementing the Bui dam with specific issues of contention at the time. The method used in this paper is not as detailed an assessment as the assessment process of the hydropower sustainability assessment protocol (HSAP) of the international hydropower association (IHA). Instead, the method makes use of a minimum number of indicators of key interest to sustainable planning and the implementation of the hydropower plant (Bui dam in this case). The comprehensive nature of HSAP of IHA is well established around the globe. A disadvantage, however, is that the HSAP of IHA is data-intensive and most often a more qualitative approach to describing sustainability. More importantly, it lacks a mathematical framework and only trained assessors will master the assessment process. The method used in this paper has a mathematical framework, has flexible choice of indicators, and the results can be described as a quantitative measure of sustainability on a scale of 0 to 1. This we find important for both pre-feasibility assessment and actual assessment of sustainability, and it is a key improvement that will simplify the assessment process for hydropower plants.
4. Under the impacts of seasonal climate changes, the Bui dam will have a high sustainability index for OND (> 0.7) season and lower sustainability indices for JFM, AMJ, and JAS (< 0.5) seasons. Per the estimations of this work, Bui dam is susceptible to predicted climate change impacts and may be water-stressed during the JFM, AMJ, and JAS seasons. The reason for this is that the impact of climate change was completely neglected in the planning stages of the dam design. Only the maximum possible flooding, which does not account for climate change impacts, has been taken into account when designing the dam. The actual capability of the Bui dam is to produce power on demand. It is expected to generate an average of 112 MW per day in order to produce power throughout the year, and has a long-term generation potential of 969 GWh/year. As a dam with storage, the Bui dam will have to store water in the JAS season and OND season to manage throughout the year until the beginning of the wet season. Two climate extremes are envisaged when climate change impacts are felt: flooding or drought. In either case, water availability for the JAS season and the OND season is more probable compared to JFM season and AMJ season. The index values indicate that the probable season when Bui dam is likely to be most sustainable in terms of operation is the OND season. The method applied in this study, makes it possible to build mathematical descriptions of climate change to assess the seasonal climate change impacts on a hydroelectric dam.

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Appendix A

Table A1. Data collected by questionnaire.

Theme on Questionnaire	Specific Information Collected
Background Information on respondents	Gender, age, level of education attained, residential status, marital status, family size
Impact of the Bui dam project on social well-being	Average monthly income, access to electricity, electricity bills
Impact of the Bui dam project on farming	Farmland, income level, degree of impact
Impacts of the Bui dam project on fishing	Seasonal income levels at pre- and post-inundation periods
Satisfaction with the Bui dam project	Satisfaction at pre- and post-construction periods of the dam
Potential for conflict	Relationship between resident and immigrant fishermen, restriction of fishermen by guards of BPA reservoir and wildlife commission of BNP, reaction by fishermen

Appendix B

Table A2. Data on interviewees.

Resettlement Part	Name of Community	Total Number of Household	Numberof Respondents	Number of Men	Number of Women
	Agbadzikurom	22	13	7	6
RPA	Brewohodi	10	6	4	2
	Damsite	6	4	1	3
	Lucine	4	8	5	3
Total		**42**	**31**	**17**	**15**
	Akanyakrom	63	51	34	17
RPB	Bui	42	32	25	7
	Dogokyina	36	23	13	10
Total		**141**	**106**	**72**	**34**

Appendix C

Table A3. Criteria for assessment.

Score	State of Component	Interpretation
0	Not done	No objective evidence on ground for assessment
≤0.25	At most 25% complete	Very little evidence/unsatisfactory
≤0.5	At most 50% complete	Significant evidence/significant gaps
≤0.75	At most 75% complete	Significant evidence/near completion
1	Complete	Objective evidence on successful completion

Appendix D

Table A4. Results of assessment procedure.

ITEM	RPB	RPA	OL1	OL2	BPA	Authors
Housing unit	1.00	1.00	1.00	1.00	1.00	1.00
Community infrastructure						
KVIP toilette facilities	0.00	1.00	0.00	0.00	1.00	0.75
Hand pump boreholes	1.00	1.00	1.00	1.00	1.00	1.00
Infrastructure for new township						
School (Primary and JHS)	1.00	0.75	1.00	1.00	1.00	1.00
Street light	0.25	0.25	0.25	0.00	0.50	0.50
Clinic	0.40	0.50	0.40	0.35	0.50	0.50
Market stall	0.00	0.00	0.00	0.00	1.00	0.25
Police station	0.00	0.00	0.00	0.00	0.00	0.00
Lorry park	0.00	0.00	0.00	0.00	0.00	0.00
Community center	1.00	0.00	1.00	1.00	1.00	1.00
Religious building	0.25	0.00	0.50	0.00	1.00	0.25
Income support						
Resettlement grant (GHc 100.00)	1.00	1.00	1.00	1.00	1.00	1.00
Land development grant (GHc 50.00)	1.00	1.00	1.00	1.00	1.00	1.00
Compensation for economic asset	0.25	0.25	1.00	0.50	1.00	0.50
Alleviation of reduction in income	1.00	1.00	1.00	1.00	1.00	1.00
Compensation for acquired lands	N/A	N/A	N/A	N/A	N/A	N/A
Livelihood improvement	0.20	0.20	0.20	0.05	0.20	0.20
Average	0.52	0.50	0.58	0.49	0.76	0.62

NA—Not Assessed; Total number of items Assessed—17; Unassessed—1; Number of items with consistent response—9; Number of items with inconsistent response—7; Number of items assessed by evidence-based assessment—7; Authors' Assessment—Evidence-based assessment; OL1—Opinion Leader 1; OL2—Opinion Leader 2; BPA—Bui Power Authority.

References

1. Afgan, N.H.; Carvalho, M.G.; Hovanov, N.V. Energy System Assessment with Sustainability Indicators. *Energy Policy* **2000**, *28*, 603–612. [CrossRef]
2. Gadonneix, P.; de Castro, F.B.; de Medeiros, N.F.; Drouin, R.; Jain, C.P.; Kim, Y.D.; Ferioli, J.; Nadeau, M.J.; Sambo, A.; Teyssen, J.; et al. *Pursuing sustainability: 2010 Assessment of country energy and climate policy*; World Energy Council: London, UK, 2010.
3. Wang, J.-J.; Jing, Y.-Y.; Zhang, C.-F.; Zhao, J.-H. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renew. Sustain. Energy Rev.* **2009**, *13*, 2263–2278. [CrossRef]
4. Afgan, N.H.; Carvalho, M. G. Sustainability Assessment in Thermal Engineering. Available online: http://lib.iutoic-dhaka.edu/greenstone/collect/seminar/index/assoc/HASH01b5/db88704a.dir/doc.pdf (accessed on 7 March 2017).
5. Locher, H.; Scanlon, A. Sustainable Hydropower-Issues and Approaches. In *Hydropower—Practice and Application*; Samadi-Boroujeni, H., Ed.; InTech Open Access Publisher: Rijeka, Croatia, 2012; pp. 1–23.
6. Boyle, G.; Everett, R.; Ramage, J. *Energy Systems and Sustainability*; Oxford University Press: Oxford, UK, 2003.
7. Santoyo-Castelazo, E.; Azapagic, A. Sustainability assessment of energy systems: integrating environmental, economic and social aspects. *J. Clean. Prod.* **2014**, *80*, 119–138. [CrossRef]
8. Assefa, G.; Frostell, B. Social sustainability and social acceptance in technology assessment: A case study of energy technologies. *Technol. Soc.* **2007**, *29*, 63–78. [CrossRef]
9. Vera, I.A.; Langlois, L.M.; Rogner, H.H.; Jalal, A.I.; Toth, F.L. Indicators for sustainable energy development: An initiative by the International Atomic Energy Agency. *Nat. Resour. Forum* **2005**, *29*, 274–283. [CrossRef]
10. Ness, B.; Urbel-Piirsalu, E.; Anderberg, S.; Olsson, L. Categorising tools for sustainability assessment. *Ecol. Econ.* **2007**, *60*, 498–508. [CrossRef]
11. La Rovere, E.L.; Soares, J.B.; Oliveira, L.B.; Lauria, T. Sustainable expansion of electricity sector: Sustainability indicators as an instrument to support decision making. *Renew. Sustain. Energy Rev.* **2010**, *14*, 422–429. [CrossRef]

12. Afgan, N.H. Sustainability paradigm: intelligent energy system. *Sustainability* **2010**, *2*, 3812–3830. [CrossRef]
13. Liu, G. Development of a general sustainability indicator for renewable energy systems: A review. *Renew. Sustain. Energy Rev.* **2014**, *31*, 611–621. [CrossRef]
14. UN General Assembly. *Transforming our world: the 2030 Agenda for Sustainable Development*; United Nations General Assembly: New York, NY, USA, 2015.
15. Hensengerth, O. *teraction of Chinese Institutions with Host Governments in Dam Construction: The Bui Dam in Ghana*; Dt. Institute for Development Policy: Bonn, Germany, 2011.
16. Obour, P.B.; Owusu, K.; Agyeman, E.A.; Ahenkan, A.; Madrid, À.N. The impacts of dams on local livelihoods: A study of the Bui Hydroelectric Project in Ghana. *International J. Water Resour. Dev.* **2016**, *32*, 286–300. [CrossRef]
17. World Rainforest Movement. Ghana: What's hidden behind the Bui dam project? In *Dams: Struggles against the Modern Dinosaurs*; Fonseca, H., Ed.; World Rainforest Movement Secretariat: Montevideo, Uruguay, 2003; pp. 24–26.
18. McCully, P. Ghana Reservoir Would Be Major Greenhouse Gas Emitter, 2008. Available online: https://www.internationalrivers.org/resources/ghana-reservoir-would-be-major-greenhouse-gas-emitter-1894 (accessed on 1 September 2016).
19. Wolfram, L.; Constanze, L.; Barnabas, A.; Laube, W.; Leemhuis, C.; Amisigo, B. Impact of Climate Change on the Black Volta Basin and the Bui Dam. GLOWA Volta Policy Brief. Available online: https://www.internationalrivers.org/sites/default/files/attached-files/glowa_volta_policy_brief_bui_dam_17_03_08.pdf (accessed on 13 March 2017).
20. Raschid-Sally, L.; Twum-Korangteng, R.; Akoto-Danso, E.K.; Raschid, L.; Koranteng, R.T.; Kyei, E.; Danso, A. *Research, Development and Capacity Building for the Sustainability of Dam Development with Special Reference to the Bui Dam Project*; Issue paper prepared for the Ghana Dams Forum February 2008; International Water Management Institute (IWMI): Colombo, Sri Lanka, 2008.
21. Urban, F.; Nordensvard, J.; Siciliano, G.; Li, B. Chinese Overseas Hydropower Dams and Social Sustainability: The Bui Dam in Ghana and the Kamchay Dam in Cambodia. *Asia Pac. Policy Stud.* **2015**, *2*, 573–589. [CrossRef]
22. Bui Power Authority (BPA). Project Milestones. Available online: http://www.buipower.com/node/7 (accessed on 29 August 2016).
23. Dietz, T.; Rutten, M.; van den Bergh, M.; Foeken, D.; Hees, S.; Hemsteede, R.; Jarawura, F.; Nijzink, L.; Seuren, G.; Veldkamp, F. *Water Dynamics in the Seven African Countries of Dutch Policy Focus: Benin, Ghana, Kenya, Mali, Mozambique, Rwanda, South Sudan*; African Studies Centre: Leiden, The Netherlands, 2014.
24. Environmental Resource Management (ERM). *Environmental and Social Impact Assessment of the Bui Hydropower Project*; Environmental Resource Management (ERM): London, UK, 2007.
25. Alhassan, H.S. Viewpoint—Butterflies *vs*. Hydropower: Reflections on large dams in contemporary Africa. *Water Altern.* **2009**, *2*, 148–160.
26. Kuunifaa, C.B. The Prevalence and Transmission of Onchocerciasis in the Black Volta Basin: A Case Study of Some Communities within the Bui Dam Environ, Ghana. Master's Thesis, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, June 2013.
27. Bui Power Authority (BPA). Legal Status. Available online: http://www.buipower.com/node/1 (accessed on 29 August 2016).
28. Alhassan, E.H. Hydro-Biology and Fish Production of the Black Volta Near the Bui Dam During the Pre and Post Impoundment Periods. Ph.D. Thesis, University of Ghana, Accra, Ghana, 2013.
29. Bui Power Authority (BPA). Resettlement Communities. Available online: http://www.buipower.com/node/14 (accessed on 29 August 2016).
30. Wu, W.-F.; Hsu, Y.; Chang, Y.-J.; Chen, Y.-C. Selection of Renewable Energy Based on Life Cycle Assessment and Multi-Criteria Decision Making. *Open J. Energy Effic.* **2016**, *5*, 1. [CrossRef]
31. Afgan, N.H.; Carvalho, M.G. Multi-criteria assessment of new and renewable energy power plants. *J. Clean Energy Technol.* **2002**, *27*, 739–755. [CrossRef]
32. Hirschberg, S.; Bauer, C.; Burgherr, P.; Dones, R.; Schenler, W.; Bachmann, T.; Gallego Carrera, D. *Environmental, Economic and Social Criteria and Indicators for Sustainability Assessment of Energy Technologies*; New Energy Externalities Developments for Sustainability Deliverable No. D3.1–RS2b; New Energy Externalities Developments for Sustainability (NEEDS): Brussels, Belgium, 2007.

33. International Hydropower Association. *Hydropower Sustainability Assessment Protocol*; IHA: London, UK, 2011.
34. De Souza, A.C.C. Assessment and statistics of Brazilian hydroelectric power plants: Dam areas versus installed and firm power. *Renew. Sustain. Energy Rev.* **2008**, *12*, 1843–1863. [CrossRef]
35. Intergovermental Panel on Climate Change (IPCC). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Institute for Global Environmental Strategies (IGES): Kanagawa, Japan, 2006.
36. Bui Power Authority (BPA). Bui Power Authority Resettlement Programme. Available online: http://www.buipower.com/node/13 (accessed on 7 February 2017).
37. Mortey, E.M. Sustainability Assessment of the Bui Hydropower System. Master's Thesis, West Africa Science Service Center on Climate Change and Adapted Land Use (WASCAL), Universite Abdou Moumouni de Niamey, Niamey, Niger, November 2015.
38. Ghana Grid Company Limited (GRIDCo). *2013 Electricity Supply Plan*; Ghana Grid Company Limited (GRIDCo): Tema, Ghana, 2013.
39. Ghana Grid Company Limited (GRIDCo). *2014 Electricity Supply Plan*; Ghana Grid Company Limited (GRIDCo): Tema, Ghana, 2014.
40. Dinis Gaspar, P.; Pedro Mendes, R.; Carrilho Gonçalves, L. Criteria Assessment of Energy Carrier Systems Sustainability. In *Energy Efficiency—A Bridge to Low Carbon Economy*; Morvaj, Z., Ed.; InTech: Rijeka, Croatia, 2012.
41. Hovanov, N. Decision Support System APIS for MEAD: Advanced User Guide. *Decis. Support Syst.* **2008**, *4*, 376–387.
42. Leys, C.; Ley, C.; Klein, O.; Bernard, P.; Licata, L. Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median. *J. Exp. Soc. Psychol.* **2013**, *49*, 764–766. [CrossRef]
43. Hovanov, N.V.; Hovanov, N.K. The Official Registration Certification of Computer Program "Analysis and Synthesis of Parameters under Information Deficiency (ASPID-3W)". Russian Federal Computer Programs Legal Safeguard Agency (RosAPO): Moscow, Russia, 1996.
44. Bui Power Authority (BPA). FAQs. Available online: http://www.buipower.com/node/12 (accessed on 7 February 2017).
45. Steinhurst, W.; Knight, P.; Schultz, M. *Hydropower Greenhouse Gas Emissions—State of the Research*; Report; Energy Economics, Inc.: Cambridge, UK, 2012. Available online: https://www.nrc.gov/docs/ML1209/ML12090A850.pdf (accessed on 17 March 2017).