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Evaluation of choices for sustainable rural electrification in developing countries: a multicriteria approach

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Abstract:

Rural electrification (RE) can be modelled as a multifactorial task connected to a large number of variables: decision makers need to choose the appropriate options by considering not only the techno-economic competitiveness but also socio-cultural dynamics and environmental consequences, making the task intricate. Many rural electrification projects have failed due to lack of attention to the issues beyond financial and technical dimensions. This paper presents a standardized approach for decision making concerning the extension of electricity services to rural areas. This approach first determines whether the supply provision should be grid expansion or off-grid on the basis of levelized cost of delivered electricity. If the grid expansion is found nonviable over off-grid options then a multicriteria decision aiding tool, SMAA-2 (Stochastic Multicriteria Acceptability Analysis), will evaluate off-grid technologies by aggregating 24 criteria values. While applying this approach, the delivered costs of electricity by the grid in remote areas within the 1-25 km distances vary in a range of 0.10-7.85 US\$/kWh depending on the line lengths and load conditions. In the off-grid evaluation, the solar PV

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(Photovoltaic) and biogas plants are found as the most preferable alternatives with 59% and 41% acceptability in their first rank, respectively.

Keywords: Off-grid supply, Multicriteria, Rural electrification

1. Introduction

Rural electrification is an essential element in bringing about social and economic developments of the under-privileged rural population. Currently 1 300 million people around the world do not have access to electricity and 85% of them live in rural areas (IEA, 2011). Rural electrification is characterized with many challenging factors such as low load density, poor load factor, rough terrain, and high capital and operating costs. The main economic activity in rural areas is agriculture, which limits productive uses of electricity, and consumers are often poor (Mohan, 1988). The low load densities result in high cost for each unit of electricity, but it should be affordable for relatively poor customers. This dilemma makes rural electrification a complex task than a urban electrification project (World Bank, 2008). In fact, rural electrification needs to involve rural community and societal dynamics instead of just implementing a technical matter of stringing lines (Barnes, 2007).

Rural electrification requires effective prioritization and planning to enable economic choices of technology considering socio-economics and environmental consequences. A large number of off-grid rural electrification projects have failed because the focus was given on technical installation without paying sufficient attention to the long term sustainability (Kumar et al., 2009). Case studies indicate that off-grid supply acts as a pre-electrification option, with the community continuing to aspire for grid connection. Consequently, many off-grid electrification projects are discontinued due to access to grid lines after implementing off-grid projects (Palit and Chaurey, 2011). [Reddy and Srinivas \(2009\)](#) observed that the choice of technology for rural

electrification is influenced by various actors and factors; policy and institutional framework at the macro level and household's socio-economics at the micro level.

Appropriate and multifactorial decision choices are, therefore, an integral part of long term sustainability of rural electrification projects. Kumar et al. (2009) proposed a decision making approach for planning and formulation of off-grid vis-à-vis grid connected rural electrification projects. Tshewang (2008) presented a weighted score system where a number of features (technical, regulatory, environmental and social) related to rural electricity supply options have been considered. Elisabeth (2008) argues that rural electrification success is allied with as much as 39 indicators under five dimensions namely technical, economic, social, environmental and institutional sustainability. Ilskog and Kjellström (2008) evaluated a rural electrification case using 31 indicators, with all the indicators having the same weight and each indicator scored on 1-7 scale, while 7 representing the best performance. Cherni et al. (2007) proposed a decision support system to determine an appropriate set of energy options which can provide sufficient power to fulfil local demands whilst improving users' livelihood in terms of five factors. Lahdelma et al. (1998) developed Stochastic Multicriteria Acceptability Analysis (SMAA) tool for aiding decision makers (DMs) to rank different alternatives based on criteria values. SMAA method can even handle alternatives which possess uncertain, inaccurate or missing information (what often happens for rural electrification cases) (Tervonen and Lahdelma, 2007). SMAA method has been successfully applied in a number of real life decision making problems, for example, decision support for selecting cargo site at airport hub (Menou et al., 2010), site selection for waste treatment facilities (Lahdelma et al., 2002), and choice of technologies for cleaning polluted soil (Hokkanen et al., 2000). Rural electrification decision making process is obviously a multifactorial problem; however, the multicriteria approach has not been adequately incorporated in rural electrification projects. In this study, we propose a multifactorial approach by incorporating SMAA method to support decision making on sustainable rural electrification

process and we also illustrate this approach to a rural village. This approach and data processing techniques can be applied in any site attributed by rural features for evaluating decision choices in extending electrification.

2. Methodology

The proposed approach first determines whether the electricity supply provision should be grid expansion or off-grid on the basis of levelized cost of delivered electricity. If the grid expansion is not found viable, then SMAA tool evaluate different off-grid alternatives considering 24 criteria under five sustainability dimensions. This paper showed the procedures for determining the cost of delivered electricity for both grid and off-grid options and for finding the critical line length (or circuit-km¹) for grid expansion against different off-grid alternatives. This paper also proposed, and described the criteria values and their weight preferences those to be applied in SMAA tool. The proposed criteria set are well representative of general requirements for sustainable expansion of rural electrification. Among total 24 criteria, 10 cardinal criteria values are generally applicable in rural areas, however, applicability of remaining 14 ordinal criteria values are subject to refine by endorsing the local DMs' views.

2.1 Grid or off-grid

Though it is evident by many case studies that off-grid renewable energy systems can play a vital, cost-effective role to supply electricity to the rural areas, these off-grid options are not mutually exclusive options to serve a rural area. The national or regional utility companies have often structured their grid-extension plan without excluding villages which might have potential for off-grid supply. Therefore, for the long term sustainability of off-grid system, it is required to know whether the off-grid system will be vulnerable to the future grid extension. To get relieve from this dilemma, the World Bank recommended a decision making process for examining different alternatives (Fig. 1).

Fig. 1. Off-grid rural electrification decision making process (World Bank, 2008)

The viability of grid extension depends on a number of factors such as distance to the load, anticipated load, distribution losses etc. Checking of the viability of grid expansion can be done by comparing the costs of delivered electricity against the off-grid supply costs. At any location, the costs of delivered electricity from the grid comprise of three components i.e. (a) cost of generation at the bus-bar of the generation plant, (b) cost of transmission, and (c) cost of distribution to the clients' meter.

2.1.1 Delivered cost of electricity through grid extension

Cost of generation at the plant bus bar

The levelized cost of energy generation is the preferred tool to compare different power generation technologies of unequal economic life, capital cost, efficiencies (or heat rates), and fuel costs (Short et al., 1995). The levelized cost of electricity generation ($LCOE_g$) can be calculated according to the formulae presented below (NREL, 2012).

$$LCOE_g = \frac{\sum_{i=1}^m [CRF_i \cdot I_i + E_i \phi_i^{HR} C_i^{FC} + \beta_i I_i]}{\sum_{i=1}^m E_i} \quad (1)$$

Here i represents the power generating plant ($1, 2, \dots, m$), m is the total number of power generating plants serving to the central grid, E_i is the annual electricity output at the bus bar (kWh) of plant i which can be obtained as $E_i = P_i \mu_i^{CF} (1 - s_i) \times 8760$, s_i is fraction of generated power consumed by the auxiliaries of plant i , CRF_i is capital recovery factor which is the ratio of a constant annuity to the present value of receiving that annuity for plant i of life t years and can be calculated according to [Wang et al. \(2011\)](#) as $CRF_i = \frac{r(1+r)^{t_i}}{(1+r)^{t_i} - 1}$, P_i is the rated capacity of the generator unit i in kW, I_i is the capital cost of plant i measured in (US\$/kW), ϕ_i^{HR} is the heat rate² of the plant measured in (MJ/kWh), and C_i^{FC} is the fuel cost (US\$/MJ), μ_i^{CF} is the plant capacity factor³, r is the rate of interest, and β_i is fraction of the capital cost for annual operation and maintenance of plant i .

Cost of transmission of electricity

The power grid serves to transport electric power from the generators to the low voltage distribution sub-stations. Cost of power transmission is associated with capital cost, operation and maintenance cost, and technical losses and depends on the specific power system configuration. The path travelled by electricity through the transmission network is very difficult

to trace in a large national electricity transmission network. ESMAP (2007) has summarised the levelized cost of power transmission ($LCOE_t$) for four power generation configurations on developing countries perspective (see Table 1).

Table 1 Levelized cost of electricity transmission ($LCOE_t$)

	Large scale	Small scale	Mini-grid	Off-grid
Typical generator size (kW)	50-300 MW	5-50 MW	5-250 kW	0.3-5.0 kW
Transmission costs	~0.25 US¢/kWh (100 km circuit)	~0.5 US¢/kWh (20 km circuit)	None	None

Source: ESMAP, 2007

Transmission and distribution (T&D) losses

In developing countries, the losses in electric power output from generator to customer can vary from 10% in well designed and maintained power grid to 25% or more in ordinary power grid (ESMAP, 2007). The transmission and distribution losses ($L_{t\&d}$) estimated by ESMAP for few developing countries are presented in Table 2.

Table 2 Power delivery loss rates in selected countries

Country	Transmission and distribution losses (%)	Year
India	26	2004
Philippines	13	2004
Vietnam	11	2004
Tunisia	12	2004
Zimbabwe	15	2004
Kenya	17	2004
Bangladesh	19	2009

Sources: BPDB, 2010; NationMaster, 2012

Cost of distribution of electricity

The cost of electricity distribution mainly depends on line length (circuit-km) of the distribution conductors and the size and number of distribution equipment installed. The distribution lines consist of a wide range of configurations: 3-phase 1 to 20 kV medium voltage feeders and 1 or 3-phase 110, 220, and 440V low voltage circuits (a typical illustration is shown in Fig. 2). Though 3-phase construction currently serves many rural areas around the world, most of the loads at the end of those lines remain single-phase loads. In their paper on reducing the cost of grid extension for rural electrification ESMAP (2000) recommends to maximize single-phase construction where applicable. This can save 30-40% of line costs and can satisfactorily meet all foreseeable needs of consumers. Thus, the single-phase configuration has been developed as a suitable configuration to serve the dispersed settlement of rural areas (ESMAP, 2000). The levelized cost of electricity distribution can be calculated by using the Eq. 2 presented below.

$$LCOE_d = \frac{[C_T P_{PL} / p_f + x_d(a_{11}C_{11} + a_{2w}C_{2w} + a_{4w}C_{4w})](CRF_d + \beta_d)}{8760 \times P_{PL} \psi^{LF}} \quad (2)$$

Here $LCOE_d$ is the levelized cost of electricity distribution in US\$/kWh, p_f is the power factor of transformers, C_T (US\$/kVA) is the unit capital cost of distribution transformers, x_d (km) is the total length of the electricity distribution line (circuit-km), C_{11} (US\$/km) the unit cost of 11 kV distribution line, C_{4w} (US\$/km) the unit cost of 3-phase 400 V line, C_{2w} (US\$/km) the unit cost of 1-phase 230 V line; a_{11} , a_{4w} and a_{2w} are the percent fractions of total length (circuit-km) for 11 kV, 400 V and 230 V circuits, respectively; β_d is the fraction of the total capital cost of distribution system towards annual operation and maintenance, P_{PL} (kW) is the anticipated load in the village for which the distribution system has to be designed, and ψ^{LF} (%) is the load factor (LF)⁴ in the village or cluster of villages to be served by the new distribution network.

Fig. 2. Circuits in a typical rural electric network

Cost of delivered electricity

The estimated total cost of delivered electricity $LCOE_{dl}$ (US\$/kWh) by extending the grid in the remote villages can be estimated by summing up its components using the following expression.

$$LCOE_{dl} = LCOE_g + LCOE_t + LCOE_d \quad (3)$$

2.1.2 Cost of electricity from off-grid options

The cost of electricity delivered from off-grid options ($LCOE_{dg}$) in the rural areas has been widely studied and reported in the literature. REN21 (2007) has estimated the cost of electricity supply by most common renewable energy technologies in the rural areas. REN21 suggests that several of the renewable energy technologies might be the most economical generation choices for mini-grids or standalone systems if sufficient renewable resources are available. ESMAP's (2007) technical report presents a costs review of a range of off-grid/mini-grid technologies covering a wider spectrum of capacities from 50 W to 100 kW. Several studies have also presented site specific levelized electricity supply costs for off-grid options in developing countries context (Mondal and Denich, 2010; Nandi and Ghosh, 2010; Subhes, 2012).

2.1.3 Critical or breakeven line length (circuit-km) for grid extension

The critical grid extension line length can be determined by comparing between the electricity supply costs by grid extension and off-grid options. The breakeven line length (circuit-km) is the length beyond which a stand-alone or mini-grid system has a lower cost of electricity delivered than that of the grid extension. If the site requires less line length (circuit-km) than the critical length then the grid extension appears to be more cost effective than the off-grid options. If the site, on the other hand, requires more circuit-km than the critical length then off-grid supply options would be economically preferable. The levelized cost of delivered electricity for off-grid systems are independent on the grid extension distance whereas the levelized cost for grid expansion fairly linearly increases with increase of grid circuit-km. The critical line length (or

breakeven length) x_c (km) can be calculated for n different off-grid alternatives using the Eq. 4 below.

$$LCOE_g(1+L_{t\&d})+LCOE_t+\frac{[C_T P_{PL} / p_f + x_c(a_{11}C_{11}+a_{2w}C_{2w}+a_{4w}C_{4w})](CRF_d+\beta_d)}{8760 \times P_{PL} \psi^{LF}} = LCOE_{dg,j}$$

(4)

For $j = 1, \dots, n$, where j stands for off-grid option among n different alternatives. The Eq. 4 shows that the delivered cost of electricity vary with the anticipated load to line length ratios (P_{PL} / x_d) for a local setting.

2.2 Choosing of off-grid power supply options

Multicriteria decision aiding tool

Multicriteria decision aiding (MCDA) is a methodology that helps decision makers (DMs) to choose their most preferred alternative from a discrete set $X = \{x_1, \dots, x_i, \dots, x_m\}$, where each x_i is measured in terms of multiple criteria (indicators). The methodology provides a decision model, which combines the criteria measurements with DMs' preferences to rank the alternatives. Most commonly an additive utility function is applied:

$$u(x_i, w) = \sum_{j=1}^n w_j u_j(x_{ij}), \quad (5)$$

where x_{ij} is the criteria measurement of the i^{th} alternative with respect to the j^{th} criterion, and the partial utility function $u_j(\cdot)$ transforms the criteria measurements to a scale from 0 to 1, where 0 corresponds to the worst outcome and 1 to the best. The vector of weights w represents the DM's preferences. The weights are assumed to be nonnegative and normalised. Therefore, the feasible weight space is $W = \{w \in R^n : w \geq 0 \text{ and } \sum_{j=1}^n w_j = 1\}$. Given fixed values for x_{ij} and w , the utility function determines the rank of each alternative as $\text{rank}(i, x, w) = 1 + \sum_{k \neq i} \rho(u(x_k, w) > u(x_i, w))$ where $\rho(\text{true}) = 1$ and $\rho(\text{false}) = 0$.

However, in many real life problems preference information from multiple decision makers may be difficult to obtain and most of the associated information possesses some degree uncertainty or impreciseness. Sometimes preference information can even be missing. Also, if preference information can be obtained from the DMs, it is unclear how the preferences of several DMs that disagree should be combined. To overcome these limitations, Lahdelma et al.(1998) developed Stochastic Multicriteria Acceptability Analysis (SMAA) method. Among the different variants of SMAA method, in this study we will utilize SMAA-2 (and its variant SMAA-O which can treat mixed ordinal and cardinal criteria) (Lahdelma et al., 2003).

SMAA-2 method

In SMAA, uncertain or imprecise criteria and preference information are represented by suitable (joint) probability distributions $f_X(x)$ and $f_W(w)$. Probability distributions allow very flexible modelling of different kinds of inaccurate, uncertain, imprecise, or partially missing information. Based on stochastic x and w , SMAA identifies the sets of favourable rank weights $W_i^r(x) = \{w \in W: \text{rank}(i, x, w) = r\}$ for each alternative i and rank r . The favourable rank weights are those that, given a particular stochastic outcome for criteria, place an alternative to the r^{th} rank. SMAA characterizes the favourable rank weights in terms of two descriptive measures: their relative size and midpoint (centre of gravity).

Rank acceptability index

The relative size of W_i^r is the *rank acceptability index* b_i^r , and it describes the variety of weights that place alternative i on rank r . The most acceptable alternatives are those with high acceptability for the best ranks. The rank acceptability indices are within the range $[0,1]$, where 0 indicates that the alternative will never obtain a given rank and 1 indicates that it will obtain the given rank always with any choice of weights. The rank acceptability index is computed as the expected volume of W_i^r divided by the volume of the set of all feasible weights W

$$b_i^r = E[\text{Vol}(W_i^r(x))]/\text{Vol}(W). \quad (6)$$

In particular, the first rank acceptability index b_i^1 describes the variety of weights that make the alternative most preferred. Nonzero (first rank) acceptability indices identify efficient alternatives, i.e. those that can potentially be the most preferred ones.

Central weight vector

The centre of gravity of W_i^1 is the *central weight vector* w_i^c and it characterizes typical weights that make an alternative most preferred. The central weight vectors are defined only for the efficient alternatives. The central weight vectors of different alternative can be presented to the DMs in order to help them understand how different weights correspond to different choices. The central weight vector is computed as the expected value

$$w_i^c = E[w: w \in W_i^r(x)]. \quad (7)$$

Confidence factor

The confidence factor p_i^c is defined as the probability for an alternative to be the preferred one with the preferences expressed by its central weight vector. It coincides with the first rank acceptability index subject to precise preference information $w = w_i^c$.

SMAA-O extension

SMAA-O is an extension of SMAA-2 for using ordinal measurements for some or all criteria. Ordinal measurement of a criterion means that the alternatives have been ranked with respect to the criterion (best, second best, third, etc.), but there is no information about how much better one alternative is than the other. SMAA-O maps the ordinal ranking information to cardinal information without forcing any specific mapping.

3. Case descriptions and applied data

The presented approach has been applied to a rural village Char-Lokman, Laxmipur in Bangladesh to support the choice of how to provide electricity to this village. The detailed design and staking for distribution lines for extending electricity service to this village has been done by Laxmipur Rural Electric Cooperative (LREC, 2011). The relevant design parameters of this distribution line section are presented in Table 3 and 4.

Table 3 The components of the studied line section

Components	Values
Number of Households	117
11 kV primary line	21.1 km
1-phase 230 V secondary line	2.7 km
3-phase 400 V secondary line	0.3 km
Estimated anticipated load (monthly consumption per consumer 60 kWh)	34 kW
Load factor (estimated)	28%

Source: (LREC, 2011)

By focusing on rural electrification practice in Bangladesh, approximately 50% of the distribution lines are 3-phase 11 kV, 45% are 1-phase 230 V and 5% are 3-phase 400 V lines. The power factor in rural context varies in the range of 0.80-0.90; in this study we considered this as 0.85 for obtaining transformer size in kVA from anticipated load in kW. We considered the transmission and distribution losses ($L_{t\&d}$) in Bangladesh as 19%.

Table 4 Cost components of the studied line section

Distribution network's components	Unit	Cost
Distribution transformer (11/0.230 kV)	US\$*/kVA	105
11 kV lines with poles and conductors	US\$/km	9 826
Low tension (LT) lines 1-phase with poles and conductors	US\$/km	8 715
Low tension (LT) lines 3-phase with poles and conductors	US\$/km	8 960
Source: LREC, 2011		
*1 US\$ = 70 BDT (Bangladesh Taka), 2010		

The power generation in Bangladesh is heavily depends on natural gas and 83% of its total electric power generation plants are fuelled by natural gas. From the total 4800 MW of gas based power plants, we have chosen two typical 90 MW and 110 MW plants for evaluating this proposed method. These plants represent the general characteristics of most of such plants in the country. The power production and cost data of the selected plants are presented in Table 5. The state-owned PetroBangla supplies natural gas to households, power plants, fertilizer industries etc. with subsidised prices whereas it supplies natural gas to the commercial entities with market prices. In this analysis, however, we will apply natural gas's market price for the power generation.

Table 5 Costs and generation parameters of two typical natural gas-fuelled thermal power plants

Parameters	90 MW	110 MW gas
	combined cycle	turbine cycle
	Values	Values
Generation capacity	90 MW	110 MW
Gross generation	559 GWh	369 GWh
Auxiliary consumption	6.2 %	6.5 %
Net generation at bus bar	524 GWh	345 GWh
Annual plant factor	70.94 %	42.14 %
Plant life	30 years	30 years
Capital costs	US\$ 102 million	US\$ 171 million
Gas tariffs	0.161 US\$/m ³	0.161 US\$/m ³
Operation and maintenance cost as fraction of capital cost	4 %	4 %
Calorific value of the natural gas	36 MJ/m ³	36 MJ/m ³
Overall efficiency of the plants	32.12 %	28.66 %
Heat rate of the plants	11.20 MJ /kWh	12.56 MJ /kWh

Sources: BPDB, 2010; Petrobangla, 2010

Renewable resources

Bangladesh is endowed with vast renewable energy resources such as biomass and solar insolation. In addition, small scale hydro and wind power can be considered as potential renewable energy resources for many cases (Rofiquel et al., 2008). Solar PV, wind turbines, biogas plants, and small-hydro are widely accepted options for electrification in the dispersed areas (REN21, 2007). In this paper, therefore, we will examine these renewable technologies, including a PV-wind-hybrid together with one non-renewable option- the diesel generator. The

off-grid electricity delivered costs for the case village using these technologies are presented in Table 6.

Table 6 Off-grid levelized electricity supply costs

Off-grid systems	Size range	$LCOE_{dg}$ (US¢/kWh) ^a
Solar PV	1-25 kW	50
Wind turbine	1-100 kW	25
PV-wind hybrid	1-100 kW	35
Biogas plant	1-60 kW	15
Mini-hydro	1-25 kW	30
Diesel generator	1-25 kW	20 ^b

^a Average values from the wide range of estimation.

^b Based on nonsubsidised diesel price.

Sources: ESMAP, 2007; Mondal and Denich, 2010; Nandi and Ghosh, 2010; Nandi and Ghosh, 2009; REN21, 2007; Subhes, 2012.

Justification of criteria, their values and weight preferences

Although off-grid supply can potentially be an alternative to the grid extension in many areas, many off-grid projects have also failed due to noncompliance of socio-cultural and environmental issues and conflicts with grid expansion. Therefore, rural electrification process needs to apply several criteria for ensuring sustainability and livelihood of the community. The selection of criteria is very important because the criteria should ensure the sustainability of the energy system. A joint UN publication (IAEA, 2005) has recommended 39 indicators and these well-defined indicators are suitable measures for five dimensions of sustainability: technical,

economic, social, environmental and institutional sustainability. In this study, we have compiled and proposed 24 criteria under five sustainability dimensions and these criteria potentially lead to an energy system which can retain better sustainability in terms of all 39 energy indicators.

Among the selected 24 criteria, values for 10 criteria are taken from national and international reports. The remaining 14 criteria are qualitative in nature and measurements of these criteria values are difficult and costly and depend on maturity of the services. We have scored these criteria on ordinal scale from DMs' view by consulting with decision makers from Laxmipur Rural Electric Cooperative (LREC) and with justifiable reasons and expertise knowledge. LREC reasonably represents all the major stakeholders through its elected board representatives (who represent all of the clients who comprise local politicians, community leaders, village advisors, focus groups, and general public) and through managers who represent the employees and line crews. All the selected criteria and their values are presented in Table 7.

These ordinal criteria are scored on a scale from 1 to 6 where 1 is the best value. We investigate the problem by assuming an additive utility/value function. The cardinal criteria values are scaled so that the worst value is 0 and the best value is 1. Explanation and justification of those criteria is presented in appendix A.

The SMAA simulation is performed without preference information from the DMs. The results include rank acceptability indices, and central weights & confidence factors for efficient alternatives. The rank acceptability indices indicate how widely acceptable each alternative may be. Alternatives with high acceptability for the best ranks are the most immediate candidates to be considered by the DMs. However, the DMs need to see whether they agree with the central weights of the most acceptable candidate, and if not, consider the next most acceptable solution. The confidence factors are based on a kind of sensitivity or robustness analysis. The confidence factors can be used to see if the criteria information is accurate enough for making an informed

decision. If the confidence factor is low, it indicates that the alternative cannot be reliably considered as the most preferred one.

Table 7: Alternatives and their criteria values

Sl.	Criteria	Alternatives					
		Solar PV 1-25 kW	Biogas plants 1- 25 kW	Wind turbine 1-25 kW	Small- hydro 1- 25 kW	PV- wind- hybrid 1-25 kW	Diesel gen. 1- 25 kW
Criteria values							
Technical dimension							
1	Capacity utilization factor, %	15-25	25-80	20-30	20-40	20-30	20-40
2	Compatibility with future capacity expansion	1	2	3	6	4	5
3	Compatibility with existing infrastructure	2	1	3	6	4	5
4	Availability of local skills and resources	2	1	4	6	5	3
5	Weather and climate condition dependence	4	2	5	6	3	1
6	Annual resource availability duration (h/y)	1460-2190	4320- 5760	720-2160	1440- 2160	2200- 2920	4380- 8760
Economic dimension							
7	Capital cost, US\$/W	1.5-2.0	0.8-0.9	1.1-1.5	1.4-2.2	1.5-1.85	0.15-0.30
8	Annual operation and maintenance costs (fixed), US\$/kW-y	8-48	20-50	16-58	20-40	30-42	10-20
9	Lifespan of the system, year	20	20	20	5	20	10
10	Learning rate, %	35	15	18	20	15	1
11	Current market share, %	60	7	1	1	1	30
12	Dependence on fossil fuel, %	0	0	0	0	0	100
Social dimension							
13	Public and political acceptance	1	2	3	6	4	5
14	Scope for local employment	2	1	3	5	4	6
15	Public awareness and willingness	1	2	3	6	5	4
16	Conflict with other applications	1	5	2	4	3	6
Environmental dimension							

17	Lifecycle GHG emissions, kg CO ₂ /kWh	0.053-0.217	0.01-0.05	0.013-0.040	0.006-0.045	0.04-0.06	0.893
18	Local environmental impact	1	2	3	5	4	6
Policy/regulation dimension							
19	Land requirement and acquisition	1	5	3	6	4	2
20	Emphasis on use of local resources	1	2	3	5	4	6
21	Opportunity for private participation	2	1	3	6	4	5
22	Tax incentives, %	5-10	5-15	0-5	5-10	5-15	0
23	Degree of local ownership	2	1	4	6	5	3
24	Interference with other utilities	1	3	4	6	5	2

Note: Criteria values are to be minimized except serial number 1, 6, 9, 10, 11, and 22

Sources: Afgan and Carvalho, 2002; IAEA, 2005; ESMAP, 2007; REN21, 2007; Nandi and Ghosh, 2009; Tsoutsos et al., 2009; Mondal and Denich, 2010; Nandi and Ghosh, 2010; Onat and Bayar, 2010; San Cristóbal, 2011; Subhes, 2012.

4. Results

The estimated values of levelized cost of delivered electricity by grid expansion in Bangladesh context are found to vary in a range of 0.10-7.85 US\$/kWh for 5-50 kW load and 1-25 km line lengths. The costs of delivered electricity are strongly dependent on circuit-km and anticipated loads to be served by the line sections (Fig. 3). The delivered electricity costs for a line segment of 5 kW load with 50% load factor are 0.16 US\$/kWh for 1 km and 1.65 US\$/kWh for 25 km line extension. In contrast, the delivered costs are significantly lower for higher loads, a 50 kW load can be served with the costs of 0.11 US\$/kWh and 0.25 US\$/kWh for 1 km and 25 km lines extension, respectively.

The delivered costs of electricity increase nearly linearly by line lengths (or circuit-km). However, the delivered costs depend non-linearly on the anticipated load to circuit-km ratios as shown in (Fig.4). The delivered costs increase very sharply if the anticipated load to circuit-km

ratio (P_{PL} / x_d) falls below 3. This means that, with these settings, the anticipated load should be 3 kW or higher for extending a 1 km line.

Fig. 3. Costs of delivered electricity against different grid line lengths with LF=0.50

Fig. 4. Costs of electricity delivered against anticipated load to circuit-km ratios

Critical line length for grid expansion

We have examined the critical line lengths (or circuit-km) to extend grid services to the rural area against renewable energy technologies; solar PV, biogas plants, wind turbine, PV-wind hybrid, and non-renewable technology diesel generator. The costs of delivered electricity by the grid expansion for 10, 15 and 25 kW loads are presented in Fig. 5. The load factor in Bangladesh rural electrification program varies between 20% and 80%. If a line section has load factor of 50%, the critical grid extension length (circuit-km) for 10 kW load will be 12.8 km for the off-grid supply cost of 0.50 US\$/kWh (solar PV). For off-grid supply costs of 0.35 US\$/kWh (PV-wind hybrid), the viable grid expansion distance will be maximum 7.8 km for serving a 10 kW load at load factor 0.50.

Fig. 5. Critical line lengths for grid expansion against five off-grid a

The anticipated load to circuit-km ratios (P_{PL} / x_d) for viable grid expansion against off-grid options are presented in Fig. 6. The intersections between off-grid costs lines and the grid extension curves are the least anticipated load to circuit-km ratios for viable grid expansion against off-grid alternatives. For example, the cost line for PV-wind-hybrid (LCOE=0.35) and the grid extension curve for load factor 0.50 intersects at the point of anticipated load to circuit-km ratio 1.2 kW/km, which means that the critical line length against this off-grid alternative is 1

km if the line has anticipated load 1.2 kW and critical line length will be 2 km if the line has anticipated load $1.2 \times 2 = 2.4$ kW and so on.

Fig. 6. Anticipated load to circuit-km ratios (P_{PL} / x_d) against off-grid configurations

The critical line lengths for the Char-Lokman village are 1.8 km, 5.0 km, 7.8 km, 13.9 and 23 km against off-grid costs of 0.15 US\$/kWh (biogas plants), 0.20 US\$/kWh (diesel generator), 0.25 US\$/kWh (wind turbine), 0.35 US\$/kWh (PV-wind-hybrid), and 0.50 US\$/kWh (solar PV), respectively. In fact, the village requires 24.1 km line for supplying grid electricity services. Therefore, this village will be viable for grid supply if off-grid supply cost is 0.51 or more (Fig. 7). For example, if the village can produce electricity from solar PV with production cost of 0.50 US\$/kWh then the village will no more be viable for grid expansion beyond 23 km of line length.

Fig. 7. Critical line lengths for the grid extension of the studied village for different off-grid alternatives

Ranking of the off-grid supply options

The case village is found non-viable for grid expansion against all of the off-grid options. Hence, we have then applied the second part of the methodology (i.e. SMAA-O) to examine which off-grid options would be best suited in terms of five criteria dimensions. After the simulation with SMAA-O, it gives rank acceptability indices for all the alternatives (Fig. 8). The rank acceptability indices show how often an alternative will get this rank with any preference weights. Figure 8 shows that solar PV and the biogas plant are the most attractive alternatives for the first rank with 59% and 41% acceptability, respectively. Among others, wind turbine, small-hydro, PV-wind hybrid, and diesel generator obtain zero acceptability for their first ranks. The alternatives other than solar PV and biogas plants are unlikely to be the most preferred alternatives based on the assumed decision model.

Fig. 8. Rank acceptability indices

These above rankings are obtained without any preference information and therefore, it is necessary to check that the preferences are agreed by the DMs. For this reason, we analysed the problem further. Figure 9 presents the central weights for the alternatives against all of the criteria. Table 8 shows that the alternatives solar PV and biogas plants are favoured by the weight preferences that are uniformly distributed among all of five criteria dimensions. Solar PV and biogas plant look likely to get DMs' consent. The small-hydro alternative is inefficient and therefore not present in the table. The confidence factor is another term to check the acceptability of the results. It is the probability for an alternative to be the preferred one with the preferences expressed by its central weight vector. A high confidence factor indicates that the alternative is almost certainly the most preferred one. The solar PV system and biogas plant are obtained good

confidence factor, 98% and 87%, respectively. In contrary, diesel generator and wind turbine are possessed with low confidence factors, 10% and 4%, respectively (Table 8).

Table 8 Confidence factors, and average weight for each criterion under five major criteria dimensions

Alternative	Confidence factor	Technical dimension	Economic dimension	Social dimension	Environmental dimension	Policy dimension
Solar PV	0.98	0.04	0.04	0.04	0.04	0.04
Biogas	0.87	0.05	0.04	0.04	0.04	0.04
Wind	0.04	0.02	0.04	0.08	0.07	0.03
PV-Wind	0.02	0.00	0.00	0.00	0.00	0.00
Diesel gen.	0.10	0.03	0.04	0.04	0.02	0.07

Fig. 9. Distribution of central weights for efficient alternatives

5. Discussions

Rural areas which appear to be potential for renewable off-grid supply are usually not automatically excluded from grid expansion and, in fact, many renewable off-grid projects have been abandoned due to extension of grid supply at later stage of off-grid projects. The grid expansion viability depends on line length (circuit-km), anticipated load, load factor, and costs of electricity for off-grid options. We have illustrated the delivered electricity costs by the grid for various load factors (0.1-0.8), 1-25 km line lengths, and 5-50 kW anticipated loads. The illustrations show the extent how the delivered electricity costs vary with line lengths and load conditions. We have then illustrated the critical line lengths against potential off-grid supply options. If the critical line length for a rural site is known, DMs can decide whether the site will be viable for grid expansion or not. The anticipated load to circuit-km ratios against delivered electricity costs show the maximum viable lengths for a particular anticipated demand. For example, if some line section has load density 3 kW/km for a particular configuration, it means that the grid line will be viable for 1 km extension if the anticipated load is at least 3 kW.

The critical line lengths against different off-grid costs will give decision makers a picture on how far a grid line can be viably extended. These will facilitate decisions about the suitability of grid extension into a rural area over decentralized options. Once it is established that the grid expansion will not be the viable one, the question will arise which off-grid options would be best suited in terms of sustainability dimensions. SMAA tool then provide all the alternatives with rank acceptability indices, where the alternatives with best ranks and higher acceptability are the most preferred ones.

One challenge to find the critical distances is that it depends on the renewable based off-grid electricity supply costs. Off-grid supply has not yet received broad market acceptance and the supply costs on local perspective is in many cases unavailable, inaccurate and variable. If SMAA

analysis finds a preferable off-grid option which was not the competitive alternative against the grid expansion option then SMAA's next off-grid alternative should be considered. If a village is found viable for grid expansion then there is no utilization of the second part of this approach as no concern usually arises about the vulnerability of the grid electricity services. This methodological tool and data processing techniques could be applied in any site attributed by rural features.

6. Conclusions

Rural electrification decision is a community conjugate process which needs a very close focus on all the sustainability dimensions. Once it is established that connecting an un-served community via grid extension is not justified, only then off-grid options would be considered. The required length of grid-line for the studied village is 24.1 km which is more than the critical distances against all the off-grid alternatives. Therefore, the grid extension is no more a preferable (or exclusive) option to serve this village. Through analysing the six off-grid alternatives by SMAA tool, we found that solar PV and biogas plants obtain 59% and 41% acceptability in their first ranks, respectively. None of the other alternatives are closer to these two in the first rank. These two alternatives are also supported by very uniform weights giving almost equal importance to all of the criteria dimensions, which may get DMs acceptance. Solar PV system and biogas plants obtain good confidence factors, 98% and 87% respectively. Therefore, DMs might choose solar PV (best option) or both options (best and second best) for extending electrification to this village. The alternatives wind, small-hydro, PV-wind hybrid, and diesel generator obtain nearly zero acceptability in their first ranks and they are unlikely to be suitable for electrifying this village.

Socio-environmental factors are usually overlooked in the decision choice on selecting decentralized options, which makes them imprudent against environmental and community challenges. Multicriteria decision support would enable rural electrification program to have

safeguarded itself from these challenges. This approach can potentially be used by the government utilities for expanding electricity services to the rural areas.

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Footnotes

¹*Circuit-km* is the line length in km required for extending the grid electricity services

²*Heat rate* is the thermal performance or energy efficiency of a thermal power plant for a specified period of time and measured in MJ/kWh. A power plant has heat rate 10 MJ/kWh means that 10 MJ of heat energy which is input into the engine will result in conversion to 1 kWh of electricity.

³*Plant capacity factor* is the ratio of actual output of a power plant over a period of time and its potential output if it had operated at full nameplate capacity the entire time.

⁴*Load factor (LF)* is the ratio of average load to the anticipated load of a power system over a period of time.

Appendix A

Explanations on criteria selection

Capacity utilization factor: It is the ratio of actual output produced by the system over a period to the potential output which could be produced if the system had run with full capacity over the same period. It depends on both resource availability and connected demand characteristics.

Higher capacity utilization factor ensures maximum utilization of investments, and it reduces the idleness of resources. We have obtained the values from referred literature.

Compatibility with future capacity expansion: The generating system should have the ability to accommodate the growing demand for long term sustainability. Without complying with capacity expansion, the system may lead to power shortage and thereby to failure. Solar PV, for example, can be easily scaled up if resources are available.

Compatibility with existing infrastructure: The support infrastructure such as roads, market infrastructure, household resources, training facilities etc. can affect the development of renewable energy options at different extents. For example, biogas plants can get full support from existing rural infrastructure.

Availability of local skills and resources: The lack of availability of local resources could limit the opportunity of off-grid power supply options and will cause high cost of the system.

Availability of local manpower, technicians, spare parts will not only reduce the installation and operation costs but also increase the community acceptance. Biogas plant, for example, can be developed by utilizing local skills and manpower.

Weather and climate condition dependence: The dependence on weather conditions decreases the reliability of the energy system. The weather dependence also causes requirement of larger storage system, which increases system costs. Solar power, for example, is only available in the day time and wind power is available only occasionally. Such system requires back-up and storage facilities, which increase costs. On the other hand, biogas plant and diesel generator are rarely dependent on weather variations.

Annual resource availability duration: Renewable resources are usually not available throughout all 8760 hours of the year. We have estimated the availability of resources as those durations (in hours) of the year when the resources are available to meet at least the minimum demands. Those resources, which have higher availability durations, can serve longer periods of the year. We have estimated the values based on local climate database.

Capital cost: Capital cost includes all the initial costs of the system to bring the system into operation i.e purchasing cost, installation cost etc. Lower the capital cost for per unit capacity better the option is. We have obtained this criterion values from the referred published literature.

Annual operation and maintenance costs (fixed): These costs include the expenses for maintenance of plants, salaries of the employees, transportation, rents etc. This is a widely used indicator for measuring energy systems performance. We have obtained the values from the referred published literature for different energy supply options.

Lifespan of the system: It represents the total economic life of the system. If the lifespan of the system is higher, it means the system will serve longer time than a system with lower lifespan. We have obtained the lifespan values from referred literature sources for all the options.

Learning rate: It represents the percent decrease of per unit production cost for every doubling of cumulative production volume. Systems with higher learning rates enjoy faster reduction of costs than those have lower learning rates.

Current market share: It represents the market share it holds in the same market segment. Higher market share implies higher information dissemination and easier availability of the components and services. The criterion values are obtained from referred sources.

Dependence on fossil fuel: It means by what extent the system is dependent on fossil fuel sources. A system with less dependence on fossil fuel means less pressure on fossil fuel reserves and saving of foreign currency. It is a very important factor for evaluating energy system's sustainability.

Public and political acceptance: Any development project, which conflicts with the interests of the local people, may provoke resistance. For successful implementation of an off-grid system, it should fit well into the socio-cultural context of the society. The solar PV system already gets wide acceptance from people of all walk of life.

Scope for local employment: Employing local people reduces the system's installation and operation costs. Local employment plays a role to improve socio-economics of the local community and thus increase the acceptability. Biogas plant, for instance, already creates some job facilities for the local people.

Public awareness and willingness: Public awareness is very crucial for rural energy projects. If the public is found unsupportive, the system may face many local challenges like thieving, damaging, tampering etc. Solar power has been enjoying very supportive responses from the local people.

Conflict with other applications: If the resources are already in other applications, then the system may find difficulties to get resources continuously. The wheat straws, for example, are already widely used for thatching purpose and therefore may not be fully available for combustion or digestion. On the other hand, solar and wind resources are abundant in nature, and their availability may not be restricted by other applications.

Lifecycle GHG emissions: It is the lifecycle production quantity of GHG per unit energy production by the system. Options with less GHG emission rates are better for the environment. The values are obtained from referred literature.

Local environmental impact: Any negative impact on the local community can make the system unacceptable. For example, small-hydro power can cause disturbance to the aquatic faunal populations (e.g. fish) thus results their disappearance.

Land requirement and acquisition: If the off-grid system requires substantial land area, this may provoke public resistance. Land acquisition for development projects in many cases are very challenging and time consuming. Those alternatives which require no extra land must enjoy the privilege over other alternatives that require land. Solar PV and diesel generator do not require any remarkable land.

Emphasis on use of resources: Policy incentives for using local resources reduce the administrative costs and attract the investor. Also, collection of resources might be easy if uses of local resources for energy applications are encouraged. Use of solar, wind and biogas resources is encouraged by the governments.

Opportunity for private participation: Private participation brings financial competitiveness and reduces inefficiency and corruption. Alternatives with the possibility of private investment can increase financial sustainability for the system.

Tax incentives: It is the financial incentives a system may achieve from the governments. Tax incentives cause a reduction of costs and attract investment. The criteria values are obtained from local sources.

Degree of local ownership: Renewable based electrification systems are often theoretically owned by initial fund provider, but physically owned by the end users. Private ownership

practice of the systems reduces maintenance cost, overcomes tampering, reduces overuse and maximizes benefits.

Interference with other utilities: The off-grid system should not interfere with the utility infrastructure of the locality. Installation of micro-hydropower plant, for example, may require relocation of water supply wells and pipes. This could lead to a significant increase in costs of the system.