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A methodological approach for assessing potential of sustainable agricultural residues for electricity generation: South Asian perspective

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Abstract: Lack of electricity is widespread in the rural areas of developing countries. Extensive production of agricultural crops and livestock in the rural areas simultaneously provides abundant amounts of residues every year. Although often utilized, much of the residues are left unused. They have diverse characteristics and they lay in scattered places. To explore the ways to utilize these residues in an innovative and sustainable manner, it is essential to systematically assess the actual resource availability beyond their current other uses. This paper proposes a method to quantify the residues with so-called residue characteristics factors data along with their processing techniques. This method determines the energy potential of the residues for anaerobic digestion (AD) processes instead of combustion, and correlates data directly with annual crop yields and livestock productions. The proposed method has been applied to five South Asian countries for estimating their potentials. The results show that the available agricultural residues in the rural areas of Bangladesh, India, Nepal, Pakistan, and Sri Lanka have annual electricity production potentials 680 kWh, 820 kWh, 720 kWh, 1200 kWh and 480 kWh per rural household (HH) respectively. Village-level utilization is found to be financially attractive (having per unit electricity generation cost 0.040 € kWh⁻¹) there to utilize the residues for electricity generation.

Keywords: Developing countries, Crop residues, Animal manure, Biomass, Anaerobic digestion

1. Introduction

In recent years, use of biomass as an electricity generation resource has been growing worldwide. The main reasons for choosing biomass include: i) recent developments of conversion technologies have made bioenergy in some cases competitive with fossil fuels, ii) environmental benefits provided by the modern use of biomass based energy, iii) improvement in energy security and diversity of energy supply, iv) increased employment and rural development, and v) restoration of degraded lands as a result of plantation and the potential increase in biodiversity [1]. Comparing with

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other renewable energy sources, biomass is often more economical than others, as it requires less capital investment and per unit production cost [2].

Biomass has been an important source of energy in most of the South Asian countries. Substantial amounts of fuel wood, charcoal, agricultural residues, dung and leaves are used in households and small industries [3]. Biomass has been used for cooking and heating in households and for feedstock in food, fiber, paper, and textile products in industries. Biomass fuels prefer to other fuels in rural energy consumption in the South Asian countries. However, the use of fuel-wood in the rural areas is limited due to lack of resources and competing non-fuel applications (e.g. wooden furnishers). On the other hand, the agricultural residues, which include crop residues and animal manure, provide a major part (e.g. 80% - 90%) of the cooking fuels for rural households [4]. Although the agricultural residues are used widely, their conversion efficiency is very low and a significant portion is wasted and poorly managed. The current use of the residues is also associated with drudgery and adverse health impacts on rural women and children [5]. The use of these residues in efficient and sustainable ways will not only make the resources worthwhile but also benefit the rural people and the environment. Therefore, it is essential to put forth alternatives and effective ways for utilizing these residues in addition to the conventional inefficient direct combustion. Rice husk, for example, is already in use for power generation in few Asian countries [6]. To explore the ways to improve the utilization of these residues, it is crucial to be acquainted with the actual amount that is freely available beyond their other applications.

Despite the renewable nature of the biomass, this resource faces a number of disadvantages when its utilization involves a combustion process. These disadvantages are: i) biomass has low energy density and thus large volume of feedstock is required for combustion in the boiler, ii) high moisture content causes less efficient combustion, iii) bio residues have high ash content and it easily forms a layer on the heat exchanger surface thus prohibiting heat transfer, and iv) combustion releases aerosols into the atmosphere. Biomass utilizations through thermo-chemical processes (e.g. pyrolysis and gasification) involve high capital costs [2]. On the other hand, biomass utilization through anaerobic digestion (AD) process has many advantages over other bioenergy conversion processes, including capturing and utilizing of CH_4 [7]. AD process has some limitations too, such as: i) high sensitivity of methanogenic bacteria on gas production, ii) odor due to presence of sulfurous compounds, and iii) corrosiveness with metals. In spite of few limitations, AD has been recognized as an environmentally friendly and least cost technology in rural context [8]. Although commercial-scale AD application is rare in developing countries, but huge numbers of small-scale AD systems are already in use in the rural areas of South Asian countries. ARTI (Appropriate Rural Technology Institute), for example, has installed more than 4 000 biogas plants in rural India which can utilize all kinds of starchy biomass.

The ARTI biogas plants use locally available materials and labor, which made them less expensive [9]. Grameen Shakti (a non-government organization) has installed more than 5 000 biogas plants in Bangladesh within the range of 1.6 m³ to 80 m³ sizes and served for households and communities [10].

Earlier literature has estimated potentials for various biomass resources in global [11], regional [1], [6], and national-level scales [3], [5], [12], [13] based on fuel calorific values. In the published literature, various techniques have been used to assess the potential of sustainable agricultural residues. Junginger et al. [14] has proposed a method for assessing available crop residues and that highlighted strategies for sustainable fuel supply to large scale bio-energy projects. Gomez et al. [15] presented a method for estimating the electricity generating potential from animal and human wastes in Spain. Fernandes et al. [16] estimated the potential of biomass residues in a region of Portugal by using Geographic Information Systems (GIS) counting cultivated area of each species. Bhattacharya et al. [1], Ravindranath et al. [5] and Perera et al. [12] have assessed the gross potential of non-plantation biomass in few Asian countries. These previous studies lack to present a clear standardized method for assessing sustainable residue potential based on crop and animal productions and conversion through anaerobic digestion (AD) process. The electricity production potential of the residues via AD process is also unclear in the published literature. This paper proposes a standard methodology in assessing electricity generating potential of agricultural residues (crops and manure) through Anaerobic Digestion process. Although cooking, heating and lighting might be the alternative applications of biogas, here we determine the electricity generating potential considering the scarcity of electricity, and national and international policy aspirations in support of rural electrification. We pool up the data according to this methodology and estimate the electricity generating potentials of residues in 5 South Asian countries and also validate this method in a case village. The proposed method is expected to give a reasonably correct figure about the residue potential; nevertheless, site specific data are required for more precise results.

This paper is organised as follows: Section 2 introduces the residue assessment method; sub-section 2.1 deals with crop residues, sub-section 2.2 deals with livestock manure, and sub-section 2.3 discusses the co-digestion issues. Section 3 presents some economic evaluation tools for residue utilizations in energy production purposes. Section 4 presents the applied data for five South Asian countries and one case village. Sections 5, 6 and 7 present the results, discussion and conclusions parts, respectively.

2. Residue assessment method

This section describes the procedure for quantifying the agricultural residues by data assimilation and briefly explains

the aspect that may arise during data assimilation. Agricultural residues cover a wide spectrum of leftover derived from crops and livestock such as rice straw, corn cobs, sugarcane bagasse, cattle manure, poultry dropping etc. The most significant divisions among these residues are crop residues and animal manure and their assessing techniques are different from each other.

2.1 Crop residues

The term crop residue is used to describe all the organic materials that are produced as by-products from harvesting and processing of agricultural crops. These crop residues can be further categorized into field residues and process residues. Crop residues that are generally in the field at the time of harvesting are defined as field residues (e.g. rice straw, wheat straw), whereas those co-produced during processing of the crops are called process residues (e.g. rice husk, bagasse). Field residues availability is somewhat subject to competing uses (e.g. animal fodder, thatching etc.), whereas process residues face low competitor challenges [1].

2.1.1 Gross residue amount of any crop species

Annual average yields of main crop types can be determined from the regional, country or international statistics. The corresponding field based and process based residue amounts are reached by multiplying the yields with matching residue to yield ratios (η_i^{yr}). The residue to yield ratio indicates how much residue (mass) is generated per unit of crop products of crop type i . The values of η_i^{yr} vary with several factors such as crop varieties, harvesting seasons, harvesting practices, fertilizer uses, etc. [12]. The available literature shows a considerable range in the values of η_i^{yr} for the major crops. When these ratios have been defined, the gross residue amount R_i (t y^{-1}) generated annually by the crop type i can be obtained as Eq. (1)

$$R_i = Y_i \cdot \eta_i^{yr} \quad (1)$$

where Y_i (t y^{-1}) is the annual crop yield. The amount of residues obtained from the Eq. (1) is not entirely available; rather, there are several active uses for this resource. The process residues, however, face almost no other competitors but domestic and industrial energy applications [3]. To estimate the actual potentially available energy from the residues, it is necessary to establish the present utilization pattern of the residues. Several estimations of the surplus availability factors (η^{saf}) have been presented in the literature [1], [3], [17], and [18]. Moreover, all the field residues are not recoverable rather only a portion of these can be removed from the field without adverse effects on the future yields. Considering all these factors, the annual theoretical available residue amount (field or process) R_i^{th} (t y^{-1}) for crop type i can be obtained as Eq. (2)

$$R_i^{th} = R_i \cdot \eta_i^{rrf} \cdot \eta_i^{saf} \quad (2)$$

where η_i^{rrf} is residue recovery factor (kg kg⁻¹ of residue) and η_i^{saf} is surplus availability factor (kg kg⁻¹ of residue) for field or process based residues for crop type i . The field and process based residues for any crop species i are required to obtain separately with the same Eq. (2) considering their recovery and availability factors. Each crop species eventually gives the residue amount by summing up both the residue types (field and process).

2.1.2 Residues into biogas by Anaerobic Digestion (AD)

Despite the biomass is renewable in nature, it faces a number of drawbacks when its utilization involves a combustion process. In contrast, Anaerobic Digestion process has been recognized as a least cost and environmentally friendly technology to convert biomass into biogas in rural context [8]. Therefore, it will be worthwhile to ascertain the energy potential of residues through AD to completely utilize the residues and minimize the adverse effects on the environment. Moisture content in the residues varies widely at different stages of harvesting and storage and the moisture content influences its heating value. The annual thermal potential E_i^{hcad} (GJ y⁻¹) of residues of crop type i through AD process can be determined as Eq. (3)

$$E_i^{hcad} = R_i^{th} \cdot \eta_i^{rdf} \cdot \eta_i^{vs} \cdot \eta_i^m \cdot Q_{mc} \quad (3)$$

here η_i^{rdf} is residue dryness factor (kg kg⁻¹ of residue), η_i^{vs} is ratio of volatile solid (VS) to dry matter (DM), η_i^m is biogas generation rate (m³ kg⁻¹ of VS) of crop species i and Q_{mc} (MJ m⁻³) is heating value of biogas. The total annual thermal potential of all the crops E_{all}^{hc} (GJ y⁻¹) can be calculated by summing up the annual thermal energy potentials of the residues of all crop types as given Eq. (4) below:

$$E_{all}^{hc} = \sum_{i=1}^I E_i^{hcad} \quad (4)$$

2.1.3 Available data in published literature

To establish the main characteristics of the major crops, a broad selection of literary sources were used. The resulting characteristic factors of major crops are presented in Table 1, 2. The crop species which have been considered in this study are rice, wheat, maize, jute, sugarcane, cotton, pulses, coconut, millet, and vegetables while the considered livestock are cattle, buffalo, goat, sheep, horse, and chicken. The average biogas yields per unit of volatile solid (VS) vary between 0.33 m³ kg⁻¹ and 0.35 m³ kg⁻¹ for anaerobic digestion of rice straw [19]. Volatile solid contents for wheat, barley and sugar beet residues are 0.64, 0.70 and 0.22 kg for 1 kg of residues and biogas yields are 0.36 m³ kg⁻¹, 0.27 m³

kg^{-1} and $0.37 \text{ m}^3 \text{ kg}^{-1}$ from VS, respectively [20]. A review report finds biogas yields from VS in the range of $0.30 \text{ m}^3 \text{ kg}^{-1}$ to $0.40 \text{ m}^3 \text{ kg}^{-1}$ for a wide spectrum of fruits, vegetables and crop wastes digested in the anaerobic digester [21].

Table 1- Characteristic factors of major field based residues

Field residue	Residue to crop yield mass ratio (η^{yr})	Residue recovery factor kg kg^{-1} of residue (η^{rrf})	Surplus availability factor kg kg^{-1} of residue (η^{saf})	Residue dryness factor kg kg^{-1} of residue (η^{rdf})	Ratio of volatile solid to dry matter (η^{vs})	Sources
Rice straws	1.76	0.60	0.80	0.873	0.54	[3], [12], [22]
Sugarcane tops	0.30	0.70	1.00	0.500	0.50 ^a	[3], [12]
Wheat straws	1.75	0.35	0.20	0.925	0.94	[3], [22], [23]
Jute stalks	3.00	0.35	0.50 ^a	0.905	0.50 ^a	[3]
Pulses straws	1.90	0.35	0.20	0.800	0.50 ^a	[3], [22]
Cotton stalks	2.75	0.35	0.68	0.880	0.50 ^a	[3], [22]
Maize stalks	2.00	0.60	1.00	0.880	0.50 ^a	[3], [12]
Groundnut straws	2.30	0.35	0.64	0.879	0.50 ^a	[3], [22]
Millet stalks	1.75	0.35	0.50 ^a	0.880	0.50 ^a	[3]
Vegetables	0.40	0.35	0.50 ^a	0.800	0.50 ^a	[3]

^a Note: Estimated by authors

Table 2- Characteristic factors of major process based residues

Process residue	Residue to crop yield mass ratio (η^{rr})	Residue recovery factor kg kg ⁻¹ of residue (η^{rrf})	Surplus availability factor kg kg ⁻¹ of residue (η^{saf})	Residue dryness factor kg kg ⁻¹ of residue (η^{rdf})	Ratio of volatile solid to dry matter (η^{vs})	Sources
Rice husks	0.267	0.8	0.46	0.876	0.69	[3], [12]
Rice bran	0.083	1.0	0.68	0.910	0.50 ^a	[3], [18]
Sugarcane bagasse	0.25	1.0	0.21	0.510	0.74	[3], [18]
Coconut shells	0.52	0.8	0.03	0.920	0.74	[12]
Coconut husks	1.03	0.9	0.57	0.890	0.73	[2], [12]
Maize cobs	0.27	0.8	1.00	0.850	0.50 ^a	[2], [12]
Maize husks	0.20	1.0	0.50 ^a	0.889	0.50 ^a	[3]
Groundnut husks	0.47	1.0	0.50 ^a	0.918	0.50 ^a	[3]
Saw dust	0.25	0.9	0.98	0.998	0.82	[14]

^a Note: Estimated by authors

2.2 Animal manure

Animal manure is principally composed of organic materials, moistures and ashes. Decomposition of animal manure can occur either in an anaerobic or aerobic environment. Under anaerobic conditions methane (CH₄), carbon dioxide (CO₂), and stabilised organic materials are produced. When compared with direct burning, the energy available from manure via anaerobic digestion (AD) has been presented in the Table 3. Even though the gross energy available from direct burning is high, the relatively high conversion efficiency for AD makes the useful energy higher.

Table 3- Comparison of useful energy available via direct burning and anaerobic digestion of 25 kg of fresh dung [2]

Parameters	Direct burning	Anaerobic digestion
Gross energy	43.76 MJ	19.71 MJ
Conversion efficiency	10 %	55 %
Useful energy	4.37 MJ	10.84 MJ
Manure fertilizer	None	10 kg (air dried)

2.2.1 Manure potential

The potential for generation of electricity from livestock manure can be calculated considering its transformation into biogas via anaerobic digestion. The first step for the calculation is the estimation of the number of heads of the livestock. Livestock such as cattle, buffalo, sheep, goat, and poultry are common in South Asian rural areas [24]. Data for the number of heads of each livestock can be obtained from country statistics or UN body FAOSTAT [11]. As the amount of manure generated by each livestock type has been defined, then the amount of methane gas could be estimated from their excrements. The dung production from animals depends on many factors such as body weights of the animals, type and quality of the feeds, and physiological states [15]. Literature suggests the average residue generation rates for varieties of livestock in different regions of the world [3], [25], [15]. The annual manure production M_j (t y⁻¹) of livestock species j can be obtained as Eq. (5)

$$M_j = N_j \cdot r_j^{rg} \quad (5)$$

Where N_j (in thousands) is the head count of livestock type j and r_j^{rg} (kg y⁻¹) is residue generation rate. Accessibility of the dung is an important factor, particularly where livestock are range-fed, and consequently the dung is not easily accessible. However, the dung from the cattle can be collected from the droppings at the cattle sheds which are generally stationed in the rural areas [2]. Annual thermal potential E_j^h (GJ y⁻¹) of livestock type j can thus be obtained as Eq. (6):

$$E_j^h = M_j \cdot \eta_j^{ref} \cdot \eta_j^{dm} \cdot \eta_j^{vs} \cdot r_j^{bg} \cdot Q_{hvt} \quad (6)$$

where η_j^{ref} is residue collection factor (kg kg⁻¹ of residue), η_j^{dm} is fraction of dry matter of residues (kg kg⁻¹ of residue), η_j^{vs} is the ratio of volatile solid to dry matter, r_j^{bg} is biogas generation rate (m³ kg⁻¹ of VS) of livestock species j , and Q_{hvt} (MJ m⁻³) is lower heating value of biogas. As a result, the total thermal potential of animal manure for all major species E_{all}^{hl} (GJ y⁻¹) can be calculated as Eq. (7)

$$E_{all}^{hl} = \sum_{j=1}^J E_j^h \quad (7)$$

2.2.2 Characteristics data

The characteristic values of residues, such as generation rate of each species, residue collection factors, and residue dryness factors are presented in literature sources [3], [15], [12], [26] as shown in Table 4.

Table 4- Characteristic values of livestock residues

Livestock	Residue generation rate kg d ⁻¹ dry matter	Residue collection factor kg kg ⁻¹ of dry matter (η^{rcf})	Ratio of volatile solid to dry matter (η^{rs})	Biogas generation rate m ³ kg ⁻¹ of volatile solid (r^{bg})	Sources
Buffaloes	2.52	0.50	0.79	0.30	[3], [12], [26]
Cattle	2.86	0.50	0.93	0.20	[12], [26]
Goats	0.55	0.30	0.59	0.31	[12], [26]
Sheep	0.33	0.60	0.91	0.31	[3], [15],[26]
Horses	3.00	0.10	0.87	0.16	[15], [26]
Poultry	0.04	0.90	0.46	0.18	[12], [26]

2.3 Total potentials of crop residues and manure through co-digestion

Anaerobic digestion process tends to be inefficient, when only one organic matter is used as sole substrate without external nutrients. The co-digestion of manure with ligno-cellulosic crop residues can increase the biogas production. Cantrell et al. [27] have found that co-digestion of swine manure with maize, wheat and rye residues improves the biogas production significantly. Co-digestion of crop residues with other wastes shall provide more suitable physiochemical property of feedstock and more balanced nutrients for efficient digestion which results high biogas production. Several studies have been performed on the co-digestion of various crop wastes with manure. Callaghan et al. [28] found that co-digestion of manure with other agricultural waste could obtain more methane gas production than the digestion of cattle manure alone. In addition, Li et al. [8] have evaluated the performance of the co-digestion of wastes in a completely mixed reactor and found a higher biogas yield than the individual's yield when the substrates digested separately. The thermal outputs from the co-digestion of all of the residue species are not available in the

literature. However, it is obvious from literature that co-digestion between crop and livestock residues produces more biogas than their separate digestion if optimum digester conditions (e.g. temperature, pH, organic loading rate) are maintained [29]. In this study, we assumed that the total thermal potential of crop and livestock residues E_{tot}^{hcl} (GJ y⁻¹) is equal to sum of their individual yields and can be determined by Eq. (8) as follows

$$E_{tot}^{hcl} = E_{all}^{hc} + E_{all}^{hl} \quad (8)$$

3. Economic aspect in utilizing the residue potential

The levelized cost of energy production (*LCOE*) is one of the popular tools used to evaluate the viability of an energy system [30], [31]. The *LCOE* is also used for comparing the energy generation costs of different options and thus for choosing the appropriate technology. Based on the heating value of the biogases from the possible residues, levelized cost of energy production, *LCOE* (€ kWh⁻¹) is to be determined by the Eqs. (9-11):

$$P_e = \frac{E_{tot}^{hcl}}{3.6 \times 8.76} \cdot \eta_e \quad (9)$$

$$E_e = P_e \times 8760 \times P^{cf} \quad (10)$$

$$LCOE \cdot E_e = a \cdot I + C_{O\&M} - R + C_f \quad (11)$$

where E_{tot}^{hcl} (GJ y⁻¹) is the total annual thermal potential of crop and livestock residues, P_e (kW) is the plant capacity, η_e is conversion efficiency from biogas to electricity which is around 26% for gas engine [15]. Also, E_e is annual electricity generation (kWh y⁻¹), P^{cf} is the plant capacity factor, a is annuity coefficient of capital cost, I (€) is capital cost, $C_{O\&M}$ (€ y⁻¹) is annual operation and maintenance cost, R (€ y⁻¹) is revenue from by-products and C_f (€ y⁻¹) is fuel (residue) cost.

Besides *LCOE*, the Net Present Value (*NPV*) and Internal Rate of Return (*IRR*) are the financial indicators which are used popularly for evaluation of an energy project and to create insight in the project's profitability [31], [32], [33]. The *NPV* (€) and *IRR* (%) can be obtained with the Eqs. (12-13)

$$NPV = \sum_{n=0}^N \frac{CF_n}{(1+r)^n} \quad (12)$$

$$0 = \sum_{n=0}^N \frac{CF_n}{(1+IRR)^n} \quad (13)$$

where CF_n (€) is the net cash flow of the investment at year n which can be calculated as

$CF_n = a \cdot I + C_{O\&M,n} - R_n + C_{f,n}$ and N (year) is the plant life, r (%) is the discount rate. Project whose return shows a

positive *NPV* value indicates a profitable investment. *IRR* also dictates a project's viability; if the calculated *IRR* exceeds the minimally acceptable return for the corresponding investment then the investment implies a profitable notion. The limitation of the *NPV* is that it requires a discount rate, which is difficult to obtain. In addition, *NPV* is unable to independently express the accurate rate of profitability. Despite the few limitations these two indicators are widely used for project financial analysis [31].

The cost parameters that are required for performing financial evaluation vary over size, type and location of the plant. The major equipment involved in generating electricity from residues are bio-digester and bio-gas engine. Their main cost components are capital cost, operation & maintenance cost and fuel cost. Considering the household and village level potential, we consider the plant range of 1-5 kW to produce electricity by utilizing the residues. The bio-digester technology is locally available in the rural areas whereas biogas engine within 1-5 kW sizes also appears in the markets. As it is very difficult to obtain consistent cost data for the aforementioned components, we have developed generalized equations by synthesizing the current market cost information concerning the South Asian region.

Capital cost: The capital costs of digester and gas engine have a significant effect on the overall production cost. The capital costs of the small size gas engines that are suitable for bio-gas utilization vary over the regions. The cost function equations for gas engines in the range of 1-5 kW and bio-digesters in the range of 1.6 - 77 m³ are derived by polynomial curve fitting technique from costs data obtained by reviewing the markets. The costs function equations are presented below.

$$\text{Digester cost equation: } C_d = 0.0024S_d^3 - 0.41S_d^2 + 40S_d + 241 \quad (14)$$

The above equation applies while $1.6m^3 \leq S_d \leq 77m^3$. Where C_d (€) is the digester capital cost and S_d (m³) is the digester size.

$$\text{Gas engine cost equation: } C_g = 20.07S_g^3 - 202.39S_g^2 + 727.88S_g - 234 \quad (15)$$

The above equation applies when $1kW \leq S_g \leq 5kW$. Where C_g (€) is the capital cost of gas generator and S_g (kW) is the generator size.

Operation and maintenance cost:

$$\text{Equation: } C_{O\&M} = 0.0002S_d^3 - 0.035S_d^2 + 2.72S_d + 1 \quad (16)$$

The equation applies for $1.6m^3 \leq S_d \leq 77m^3$. Above $C_{O\&M}$ (€ y⁻¹) is the operation and maintenance cost of the digester-gas engine system.

Fuel cost: For obtaining the fuel (i.e. residue) price, we modeled an equation which gives annual fuel cost C_f (€ y⁻¹) for corresponding electricity energy production. The equation is given below:

Fuel cost equation:
$$C_f = \frac{E_e \times 3.6}{\eta_t \cdot \eta_g \times 1000} \cdot C_{res} \quad (17)$$

where E_e is annual electricity generation (kWh y⁻¹), η_g (%) is the electrical efficiency of gas engine, η_t (GJ t⁻¹) is the heating value of the residues, and C_{res} is the cost of residues per tonne (€ t⁻¹)

4. Applied data

The data for annual crops and livestock production in 5 South Asian countries for 2008 were obtained from FAOSTAT [34] and presented in Table 5, 6. It can also be observed that, with few exceptions, the FAOSTAT data are quite consistent with national data when available. The financial parameters that have been applied in this study are presented in Table 7.

Table 5- Production of major crops (Tg) in five South Asian countries in 2008

	Rice	Sugarcane	Wheat	Jute	Pulses	Coconut	Cotton	Maize	Ground nut	Millet	Vegetables
Bangladesh	46.0	4.9	0.84	0.8	0.071	0.088	0.867	1.346	0.044	0.006	1.10
India	148	348	78.5	1.8	0.80	10.894	5.811	19.29	7.338	11.34	29.17
Nepal	4.2	2.5	1.6	0.0	0.025	0.000	0.017	1.878	0.0	0.291	1.01
Pakistan	10.4	64	20.9	0.0	0.121	0.008	2.011	4.035	0.085	0.296	2.54
Sri Lanka	3.8	0.80	0.0	0.0	0.0	2.200	0.0	0.112	0.010	0.006	0.06

Table 6- Head count (in millions) of major livestock in five South Asian countries in 2008

	Buffaloes	Cattle	Goats	Sheep	Camels	Horses	Poultry
Bangladesh	1.3	25.5	56.0	1.6	-	-	242
India	98.6	174.0	125.7	65.0	0.63	0.75	656
Nepal	4.5	7.1	8.2	0.8	-	-	24
Pakistan	30.0	31.8	56.6	27.0	0.93	0.35	276
Sri Lanka	0.3	1.2	0.37	-	-	-	15

Table 7- Assumptions on financial parameters

Parameters	Value
Nominal discount rate	10 % y ⁻¹
Inflation rate	5 % y ⁻¹
Life time of the project	20 years
Annual plant capacity factor of biogas plant	25 % y ⁻¹

The annual crops and livestock production for Sherpur village are obtained by conducting a local survey in all the households in that village. Each household's data are obtained from the household's owner by querying them about their annual production of crops and animal. The data that are provided by the households are based on their gross estimation of crop and animal productions. The annual crop and animal yields data for Sherpur village for the year 2010 are presented in Table 8 and 9.

Table 8- Annual crop yields (Mg) in Sherpur village in 2010

Rice	Sugarcane	Wheat	Jute	Pulses	Cotton	Maize	Groundnut	Millet	Vegetables
870	513	33	30	4.4	0.60	60	28	1.70	142

Table 9- Number of livestock heads in Sherpur village in 2010

Buffaloes	Cattle	Goats	Sheep	Horses	Poultry
77	439	738	123	2	756

5. Results

Applying the methodology presented in this paper, first we have done a country level potential assessment of the sustainable agricultural residues in the rural areas of five South Asian countries. Then we have applied this method in a remote village Sherpur located in Bogra, Bangladesh, to estimate the residue potential and evaluate the financial viability of their utilization. The country level assessment shows generalized applicability of this methodology while the case village application shows more detailed economic analysis and validity.

5.1 Potential of residues in five South Asian countries

We have assessed the net potential of sustainable agricultural residues in five South Asian countries, namely Bangladesh, India, Nepal, Pakistan, and Sri Lanka. Equations (1-8) and the characteristic factors data in Table 1, 2, and 4 have been applied to determine the total available residues from crops and livestock and their total electricity generating potential per rural household. The energy potential is determined considering the conversion of residues through Anaerobic Digestion process which is convenient in the rural areas. The number of rural households in the five countries and their corresponding average annual thermal and electrical energy potential per household are depicted in the Table 10 and presented in Fig. 1.

Table 10- The annual electricity generating potential per rural household (HH) in 5 countries

Country	Energy potential (thermal) from freely collectable agricultural residues (PJ y ⁻¹)	Electricity generating potential (TWh y ⁻¹)	Number of rural HHs (millions) [35]	Electricity potential per rural HH (kWh y ⁻¹)	Basic demand per rural HH ^a (kWh y ⁻¹)
Bangladesh	230	16.70	24.56	679	360 [36]
India	1570	113.00	138.27	820	365 [37]
Nepal	53	3.83	5.30	724	-
Pakistan	282	20.40	16.47	1238	-
Sri Lanka	22	1.56	3.26	479	360 [38]

^a Note: A hypothetical demand which is considered as a lifeline goal from the renewable energy sources in rural areas

Fig. 1- Average residue potential (electricity) per household in five South Asian countries

5.2 Application of this method to a remote village as a case study

We have applied this proposed method in a remote village Sherpur in Bangladesh to obtain the residue potential and checking their financial viability for electricity production. The selected Sherpur village is located in the bank of the big

river Jamuna. The village consists of 219 households with each comprising five family members in average. The village is far away from the national grid and it is very unlikely to be connected with the grid in future. The main livelihood of the villagers is agriculture and their living style is very simple and they do not require large amounts of electricity. These households generally require electricity for lighting, cooling, and entertaining. The average electrical load per household considering 3 energy efficient bulb (compact florescent bulb, 15 W each), 2 fans (40 W each), and 1 television (40 W) for operating 6 hours a day is about 1 kWh d⁻¹ [39]. We assumed that the operating times of all the appliances coincide in the same period. The residues will be converted to electricity through anaerobic digester and small-scale gas engine.

5.2.1 Potential per household

Using the above data and with the presented methodology, the average electricity potential per household are determined and depicted in Table 11. The characteristic data including the availability factors are taken from Table 1, 2, and 4.

Table 11- Household level potentials of agricultural residues in Sherpur village

Number of HHs	Thermal energy potential from crop residues (GJ y ⁻¹)	Thermal energy potential from livestock residues (GJ y ⁻¹)	Electricity generating potential from both crop and livestock residues (MWh y ⁻¹)	Average electricity generating potential per HH (kWh y ⁻¹)
219	3631	627	307	1404

The surplus availability factors for both crop and livestock residues found in the published literature vary over the range of 0.2 - 1.0. The site specific availability factors for each individual species are not available. Hence, we have performed a sensitivity analysis about to what extent the fractions of the availability factors affect the household level potentials (see Fig. 2).

Fig. 2- Potentials of households (HHs) as a function of residue availability factors

5.2.2 Economic analysis

5.2.2.1 Cost of energy

When considering the energy systems in question, the Levelized Cost of Energy (*LCOE*) depends on capital cost of digester and gas engine, operation and maintenance cost of the digester and gas engine system, and fuel cost. When considering the 6 hours operation per day, the capacity factor of the plant is 25% and for a 1 kW power plant it would mean 2 190 kWh of electric energy per year. We here considered, the intended electricity producers are the owner of the residues and they will provide it free of cost. The costs related to carrying and storing of the residues are included in the operation and maintenance costs of the system. By using the cost data from Equations 14-17 and residue characteristic factors data from Table 1, 2, and 4 we have calculated the *LCOE* for plants with a capacity range from 1 kW to 5 kW. The resulting *LCOE* values are presented in Fig. 3.

Fig. 3- Levelized Cost of Energy ($LCOE$) in € kWh^{-1} for 1-5 kW plants

5.2.2.2 Financial indicators (NPV and IRR)

Beside other cost functions, the financial indicators NPV and IRR are strongly depended on the electricity selling price. The electricity selling price is the hypothetical price the users intend to purchase electricity with that price considering availability and price of electricity from other sources in the perspective area.

We determined NPV and IRR for a 1 kW electric plant with electricity selling price in the range 0.03-0.14 € kWh^{-1} . The NPV was found to be zero at electricity selling price 0.040 € kWh^{-1} , and the IRR was found 10% with the same price. These two indicators mean the project is acceptable in financial terms if the electricity selling price at least 0.040 € kWh^{-1} was considered. While the electricity production prices from other 1- 100 kW scale renewable technologies such as solar PV, small wind, micro-hydro, biomass gasifier vary over the range of 0.06-0.45 € kWh^{-1} [40] and the electricity production price of off-grid diesel plant (1 kW) varies over 0.30-0.45 € kWh^{-1} [41], here the electricity production at 0.04 € kWh^{-1} from bio residues is prospective.

5.2.2.3 Effects on $LCOE$ for the variation of capital costs and residue compensation costs

The residues are primarily not intended to sell by the rural owner rather they use those in other inefficient applications. The residues are initially supposed to be supplied free of cost, however, compensations against these residues not only encourage for modern applications but also give the owner a moral boost. The capital cost of the digester and the gas generator system has also effect on the $LCOE$. It will be worthwhile to see the effects on $LCOE$ for changing the capital costs and for applying residue compensation costs. We have performed a sensitivity analysis for $\pm 20\%$ changes of the capital costs and for applying 1 € t^{-1} - 10 € t^{-1} residue compensation costs for 1 kW plant to demonstrate in what extent the $LCOE$ varies with their changes (Fig. 4). Figure 4 shows, application of the residues for electricity production can

be compensated with attractive price by accepting few increase of *LCOE*. For example, the *LCOE* for a 1 kW plant will be 0.045 € kWh⁻¹ and 0.100 € kWh⁻¹ while the project pays residue price at a rate of 1.0 € t⁻¹ and 10.0 € t⁻¹, respectively for the base (± 0 % change) capital cost. If the capital cost is increased by 20 %, the *LCOE* will be 0.054 € kWh⁻¹ and 0.107 € kWh⁻¹ for the residue price of 1.0 € t⁻¹ and 10.0 € t⁻¹, respectively. The resulting changes in *LCOE* remain relatively small even if a 20% changes in the capital costs would occur.

Fig. 4- Effects on *LCOE* for changing of capital costs, and compensation costs for residues for 1 kW plant.

6. Discussion

The novelty of the presented methodology is that it assesses the energy potential of agricultural residues through the anaerobic co-digestion process instead of direct combustion. The anaerobic digestion process is recognized as an environmentally friendly technology in the rural context offering many advantages over direct burning such as this process requires less capital cost and employ local technology, materials, and labor. AD process can convert agricultural residues into biogas, while the biogas is convertible to electricity by gas engine. The residue potentials directly correlate with annual crop and animal production levels, which is another fit of this method due to availability of annual yields data.

The thermal outputs from the co-digestion of all of the residue species are not available in the literature. However, it is obvious from literature that co-digestion between crop and animal residues produces more biogas than their separate

digestions. In our study, we determined the potentials of the residues by counting their individual contribution without considering the benefit from possible co-digestion. Thus, the actual potentials could be even higher.

The remote village Sherpur gives remarkably higher electricity potential per household than the average country level potential in Bangladesh. It is due to the fact that the village is comprehensively agriculture dependent and they produce more agriculture products than the country's average. The *LCOE* is 0.040 € kWh⁻¹ for 1 kW plant, which is attractive comparing with other renewable energy projects. As a portion of the residues is currently used by some inevitable applications, hence understandingly the whole portion of the residue may not be freely available; however, even 35% of the residues may sufficiently meet their estimated demand. Another important aspect is that, residues used for electricity production might be compensated with attractive price, although it results in somewhat increase of *LCOE*. *LCOE* of 0.045 € kWh⁻¹ would enable the project to pay residues price at a rate of 1 € t⁻¹. The 1-5 kW plant sizes are bigger for an individual rural household (i.e. 1 kWh demand per day means only 167 W peak for 6 hours a day operation), however, rural households usually stay very close each other in a rural cluster and they might share the electricity with a sort of simple wire.

The main challenge in applying this method is choosing or determining the appropriate characteristic factors data that vary significantly over geographic regions, harvesting practices, storage, ages etc. Characteristic factors data that have been used in this study represent the average values for the crop and livestock species of different harvesting methods, storages, body weights, ages, and quality of feeds. These presented data are applicable in South Asian region and they can be used for estimation of potentials of residue resources. Site specific characteristic values can be determined by using surveys or experiments in the concerned areas. The efficient co-digestion also depends on a number of technical aspects such as temperature, pH, mixing quality, loading rate, and carbon nitrogen ratio in organic materials and these factors entirely related to the particular digester settings. The digestion process also requires a sort of impurities free water which is unavailable in many areas. Site specific issues like shortage of skilled technicians for plant operation and maintenance, shortage of pure water, and lacking of facilities for residue sorting and mixing might arise when the project begins and these are not covered in this paper and need to study more in depth.

7. Conclusions

According to the estimation by this method, significant amount of bio resources are available from agricultural residues for modern energy applications in the selected South Asian countries. The estimated annual electricity potentials from the residues in Bangladesh, India, Nepal, Pakistan and Sri Lanka are about 680, 820, 720, 1200, and 480 kWh per

household, respectively and could be used to meet the basic electricity demand of rural households. The village case shows that even higher potentials are available in agriculture intensive villages. This implies a good level of attractiveness for utilizing the residues for electricity production. The characteristic values of different crops and livestock vary widely over regions. However, the collected data can be used for general estimations of residue resources. The data processing techniques and methodology could be applied in village or regional level or in any agricultural zone in South Asian countries to assess their residue potentials. Once the potentials of the residues are estimated then the investment decision can be taken based on economic viability.

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References

- [1] Bhattacharya SC, Abdul Salam P, Runqing H, Somashekar HI, Racelis DA, Rathnasiri PG, et al. An assessment of the potential for non-plantation biomass resources in selected Asian countries for 2010. *Biomass Bioenerg* 2005; 29(3):153–66.
- [2] Rao PV, Baral SS, Dey R, Mutnuri S. Biogas generation potential by anaerobic digestion for sustainable energy development in India. *Renew Sust Energ Rev* 2010; 14(7):2086–94.
- [3] K Hossain A, Badr O. Prospects of renewable energy utilization for electricity generation in Bangladesh. *Renew Sust Energ Rev* 2007; 11(8):1617–49.
- [4] Calle FR, Groot PD, Hemstock SL, Woods J, editors. *The Biomass Assessment Handbook: Bioenergy for a Sustainable Environment*. London: Earthscan; 2007.
- [5] Ravindranath NH, Somashekar HI, Nagaraja MS, Sudha P, Sangeetha G, Bhattacharya SC, et al. Assessment of sustainable non-plantation biomass resources potential for energy in India. *Biomass Bioenerg* 2005; 29(3):178–90.
- [6] Gadde B, Menke C, Wassmann R. Rice straw as a renewable energy source in India, Thailand, and the Philippines: Overall potential and limitations for energy contribution and greenhouse gas mitigation. *Biomass Bioenerg* 2009; 33(11):1532–46.
- [7] Lansing S, Martin JF, Botero RB, da Silva TN, da Silva ED. Methane production in low-cost, unheated, plug-flow digesters treating swine manure and used cooking grease. *Bioresour Technol* 2010; 101(12):4362–70.
- [8] Li R, Chen S, Li X. Biogas Production from Anaerobic Co-digestion of Food Waste with Dairy Manure in a Two-Phase Digestion System. *Appl Biochem Biotechnol* 2010; 160:643–54.

- [9] Appropriate Rural Technology Institute. Technologies [Internet]. Maharashtra-India: ARTI ; 2011. Rural Energy Technologies [cited 2011 Jun 17] ARTI Biogas Plant: A compact digester for producing biogas from food waste. Available from: <http://www.arti-india.org/>
- [10] Renewable Energy Information Network of Bangladesh. Renewable Energy Information Network [Internet]. Dhaka-Bangladesh: REIN; 2012. Database, RET projects in brief [cited 2012 Feb 3]. Available from: <http://www.lged-rein.org/lged.php>
- [11] Kim S, Dale BE. Global potential bioethanol production from wasted crops and crop residues. *Biomass Bioenerg* 2004; 26(4):361–75.
- [12] Perera KKCK, Rathnasiri PG, Senarath SAS, Sugathapala AGT, Bhattacharya SC, Abdul Salam P. Assessment of sustainable energy potential of non-plantation biomass resources in Sri Lanka. *Biomass Bioenerg* 2005; 29(3):199– 213.
- [13] Pakarinen A, Maijala P, Stoddard FL, Santanen A, Tuomainen P, Kymäläinen M, et al. Evaluation of annual bioenergy crops in the boreal zone for biogas and ethanol production. *Biomass Bioenerg* 2011; 35(7):3071–78.
- [14] Junginger M, Faaij A, van den Broek R, Koopmans A, Hulscher W. Fuel supply strategies for large-scale bio-energy projects in developing countries. Electricity generation from agricultural and forest residues in Northeastern Thailand. *Biomass Bioenerg* 2001; 21(4):259–75.
- [15] Gómez A, Zubizarreta J, Rodrigues M, Dopazo C, Fueyo N. Potential and cost of electricity generation from human and animal waste in Spain. *Renew Energ* 2010; 35(2):498–505.
- [16] Fernandes U, Costa M. Potential of biomass residues for energy production and utilization in a region of Portugal. *Biomass Bioenerg* 2010; 34(5):661–66.
- [17] Gómez A, Rodrigues M, Montañés C, Dopazo C, Fueyo N. The potential for electricity generation from crop and forestry residues in Spain. *Biomass Bioenerg* 2010; 34(5):703–19.
- [18] Prasertsan S, Sajjakulnukit B. Biomass and biogas energy in Thailand: Potential, opportunity and barriers. *Renew Energ* 2006; 31(5):599–610.
- [19] Lei Z, Chen J, Zhang Z, Sugiura N. Methane production from rice straw with acclimated anaerobic sludge: Effect of phosphate supplementation. *Bioresour Technol* 2010; 101(12):4343–8.
- [20] Murphy JD, Power N. Technical and economic analysis of biogas production in Ireland utilizing three different crop rotations. *Appl Energ* 2009; 86(1):25–36.
- [21] Nallathambi GV. Anaerobic digestion of biomass for methane production: A review. *Biomass Bioenerg* 1997; 13(1):83–114.

- [22] Singh J, Panesar BS, Sharma SK. Energy potential through agricultural biomass using geographical information system: A case study of Punjab. *Biomass Bioenerg* 2008; 32(4):301–7.
- [23] Karellas S, Boukis I, Kontopoulos G. Development of an investment decision tool for biogas production from agricultural waste. *Renew Sust Energ Rev* 2010; 14(4):1273–82.
- [24] Rofiqul IM, Rabiul IM, Rafiqul AM. Renewable energy resources and technologies practice in Bangladesh. *Renew Sust Energ Rev* 2008; 12(2):299–343.
- [25] Karaj S, Rehl T, Leis H, Müller J. Analysis of biomass residues potential for electrical energy generation in Albania. *Renew Sust Energ Rev* 2010; 14(1):493–99.
- [26] Bhattacharya SC, Thomas JM, Abdul Salam P. Greenhouse gas emissions and the mitigation potential of using animal wastes in Asia. *Energy* 1997; 22(11):1079–85.
- [27] Cantrell KB, Ducey T, Ro KS, Hunt PG. Livestock waste-to-bioenergy generation opportunities. *Bioresource Technol* 2008; 99(17):7941–53.
- [28] Callaghan FJ, Wase DAJ, Thayanithy K, Forster CF. Co-digestion of waste organic solids: batch studies. *Bioresource Technol* 1999; 67(2):117–22.
- [29] Khalid A, Arshad M, Anjum M, Mahmood T, Dawson L. The anaerobic digestion of solid organic waste. *Waste Manage* 2011; 31(8):1737–44.
- [30] Diaf S, Diaf D, Belhamel M, Haddadi M, Louche A. A methodology for optimal sizing of autonomous hybrid PV/wind system. *Energy Policy* 2007; 35(11):5708–18.
- [31] Short W, Packey DJ, Holt T. A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies. Golden (CO): National Renewable Energy Laboratory; 1995 March, 124 p, [Report](#) No. TP-462-5173
- [32] Rothwell GS, Gomez T, editors. Electricity economics: regulation and deregulation. NJ: John Wiley and Sons; 2003.
- [33] Zamalloa C, Vulsteke E, Albrecht J, Verstraete W. The techno-economic potential of renewable energy through the anaerobic digestion of microalgae. *Bioresource Technol* 2011; 102(2):1149–58.
- [34] FAOSTAT [database on the Internet]. Rome-Italy: Food and Agriculture Organization of the United Nations; 2010- [cited 2010 Aug 15] Production, Livestock Primary; Available from <http://faostat.fao.org/> Files updated annually.
- [35] United Nations Development Programme. UNDP around the world [Internet]. NY:UNDP; 2011. Country, Country Information [cited 2011 Aug 22]; Available from: <http://www.undp.org/>

- [36] Ministry of Power, Energy and Mineral Resources of Bangladesh. National Energy Policy-2004. Dhaka-Bangladesh: The Powercell; 2004 May.
- [37] Ministry of Power of India. Rural Electrification Policy. New Delhi-India: The Gazette of India; 2006 Aug. Memorandum No.44/26/05-RE (Vol-II).
- [38] Ministry of Power and Energy, Government of Sri Lanka. Ministry of Power and Energy [Internet]. Colombo: National Energy Policy and Strategies of Sri Lanka; 2008 [cited 2011 Jul 29]. Available from: <http://power.lk/downloads/>
- [39] Mondal AH, Denich M. Hybrid systems for decentralized power generation in Bangladesh. Energy Sustain Dev 2010; 14(1):48–55.
- [40] REN21. Renewables 2007 Global Status Report. Paris-France: Renewable Energy Policy Network for the 21st Century and Washington, DC: Worldwatch Institute; 2008.
- [41] ESMAP. Technical and Economic Assessment of Off-grid, Mini-grid and Grid Electrification Technologies. Washington, DC: Energy Sector Management Assistance Program; 2007 Dec. ESMAP Technical Paper 121/07.