METHODOLOGY FOR ESTIMATING BIOMASS ENERGY POTENTIAL AND ITS APPLICATION TO COLOMBIA

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ABSTRACT

This paper presents a methodology to estimate the biomass energy potential and its associated uncertainty at a country level when quality and availability of data are limited. The current biomass energy potential in Colombia is assessed following the proposed methodology and results are compared to existing assessment studies.

The proposed methodology is a bottom-up resource-focused approach with statistical analysis that uses a Monte Carlo algorithm to stochastically estimate the theoretical and the technical biomass energy potential. The paper also includes a proposed approach to quantify uncertainty combining a probabilistic propagation of uncertainty, a sensitivity analysis and a set of disaggregated sub-models to estimate reliability of predictions and reduce the associated uncertainty. Results predict a theoretical energy potential of 0.744 EJ and a technical potential of 0.059 EJ in 2010, which might account for 1.2% of the annual primary energy production (4.93 EJ).

Keywords: bio-energy, biomass, energy potential, review, Colombia, estimation

NOMENCLATURE

Abbreviations

CHP	Combined Heat and Power
CI	confidence interval
EUD	extended uniform distribution
FFB	fresh fruit bunch
MSW	municipal solid waste
R&D	Research and Development
UPME	Unidad de Planeación Minero Energética

Symbols

a	availability factor
b	biogas yield from manure
c	by-product to product ratio in forestry
d	dry basis
f	manure production per head
k	by-product to product ratio in agriculture
H	heads, animal stocks
HHV	higher heating value
LHV	lower heating value
M	moisture content
N	number of references
P	production
Q	theoretical energy potential

doi: 10.1016/j.apenergy.2014.07.004

Q^T	technical energy potential
w	wet basis
$\overline{x}$	mean of x
α	constraint factor to calculate availability
β	width factor for EUD distribution
σ	standard deviation
η	energy efficiency
ρ	density

Subscript

AR	agricultural residue
AW	animal waste
current	state-of-the-art technology
F	forestry
i	i-th agricultural crop
j	j-th residue for each i-th agricultural crop
m	m-th type of animal
modern	future technology
n	n-th sub-category of type of animal
r	r-th forestry resource
s	s-th biofuel
x	x-th type of urban waste
U	urban waste

1. INTRODUCTION

Global interest on biomass as the largest renewable resource today [1] with the potential to reduce dependency on fossil fuels and decrease greenhouse gas emissions continues to grow. Today biomass is primarily used in developing countries as an energy source for cooking and heating. To a lesser extent, biomass is employed in industrialized countries to supply heat, combined heat and power (CHP) and biofuels. In the future, biomass demand is likely to increase as population grows, cost-effective technologies become available and various countries promote policy mechanisms [1]-[3]. However, significant challenges need to be addressed to make use of biomass and bioenergy. Hurdles include land use competition, direct and indirect land-use change, deforestation, crops for food vs. biofuels, pressure on water resources, etc.

In order to ensure a sustainable exploitation of biomass resources in the future, governmental and industrial efforts will be required in developing countries and emerging economies in Africa, Asia and Latin America. These efforts include diffusing best agricultural practices, modernizing agriculture and bioenergy technology, as well as promoting national and regional policies [4]. It is therefore essential to formulate well-structured and strategic approaches to exploit biomass resources. This paper deals with one of the critical challenges to exploit biomass in a country: how to estimate the current biomass energy potential. This challenge is further complicated in developing countries where availability and quality of data is limited. This paper presents a methodology to estimate the biomass energy potential and its associated uncertainty at a country level when availability and quality of data are limited. It is therefore an extension of the methodology proposed by authors to estimate the current biomass energy potential at a country level in Ref. [5], and it also relates to a methodology published by authors to assess the future biomass energy potential in a country (see Ref. [6]). The proposed methodology is a bottom-up resource-focused approach with statistical analysis that uses a Monte Carlo algorithm to stochastically estimate the theoretical and the technical biomass energy potential. It includes a proposed approach to quantify uncertainty combining a probabilistic propagation of uncertainty, a sensitivity analysis and a set of disaggregated sub-models to estimate reliability of predictions and reduce the associated uncertainty. The current biomass energy potential in Colombia is assessed following the proposed methodology and results are compared to existing assessment studies.

Potential advantages of the proposed methodology include transparency, reproducibility, low cost and possible adaptability to analyze other countries. This paper is structured as follows: section 2 presents a literature review of state-of-the-art methodologies to assess biomass energy and address uncertainty. Section 3 describes the proposed methodology, while section 4 presents the application of the proposed methodology to the case study of Colombia. Finally, conclusions and recommendations are presented in section 5.

2. LITERATURE REVIEW

2.1 State-of-the-art methodologies

Detailed comparison of approaches, methodologies, key drivers and results of state-of-the-art biomass energy assessment for different countries are provided by Batidzirai et al. [7], Heistermann et al. [8], Berndes et al. [9], Gnansounou [10] and Van Schrojenstein Lantman J et al. [11]. Batidzirai et al. [7] suggest three key elements to categorize state-of-the-art assessments: the type of potential, the type of approach and the type of methodology. Four types of potentials exist, namely theoretical potential (maximum amount of biomass), technical potential (fraction of the theoretical potential available at current conditions and constraints), the ecologically sustainable potential (fraction of technical potential under restrictions related to nature conservation and preservation of soil, water and biodiversity) and market potential (fraction of the technical potential that satisfies certain economic criteria). Similarly, three types of approaches are identified: resource-focused, demand-driven and integrated. While resource-focused approaches estimate the overall biomass resources and competition among different uses, demand-driven assessments investigate the cost competitiveness of biomass and bioenergy systems and evaluate biomass supply to meet exogenous targets. Integrated approaches combine features of both approaches and offer the possibility to evaluate multiple sustainability aspects. Finally, various types of methodologies are employed depending on the type of approach. Two main types of methodologies are commonly employed in resource-focused approaches as defined by Batidzirai et al. [7]:

- Statistical analysis (non-spatial specific): it relies on statistical data to estimate the availability of biomass for energy conversion and other uses. Advantages include simplicity, transparency, reproducibility and low cost. However, it offers limited considerations for macro-economic impacts, environmental and social aspects.
- Spatially explicit analysis: it combines spatially explicit data and land use to assess biomass energy potential. The main advantage is the ability to evaluate distribution of biomass and impacts at a local and regional level. Drawbacks include lack of reproducibility, labor intensiveness and high complexity that does not necessarily provide more accurate results.

Likewise, two main types of methodologies are employed in demand-driven assessments [7]:

- Cost-supply analysis: it combines a biomass energy technical estimation with a cost evaluation of the biomass supply chain. It is a simple transparent, reproducible and inexpensive method. However, competition is not accurately modeled as it does not allow matching demand and supply through prices.
- Energy-system modeling: it simulates the behavior of energy markets and the competitiveness of biomass energy systems through application of economic optimization. Benefits include suitability to evaluate costs and effectiveness of policies. However, it lacks validation of land availability and agricultural yields and it uses economic correlations based on expert judgment.

3. METHODOLOGY

The proposed methodology is formulated under four equally important criteria: 1) it should be easy to implement and to be reproduced, 2) it should be inexpensive to adapt to constrained R&D budgets, 3) it should be able to estimate the theoretical and the technical biomass energy potential at a country level and 4) it should be able to estimate uncertainty in predictions when availability and quality of data are limited. Thus, it is proposed to use a bottom-up resource-focused approach with statistical analysis as it satisfies criteria 1 and 2. To satisfy criterion 3, this approach is configured to stochastically estimate the theoretical and the technical biomass energy potential of relevant biomass categories. In order to satisfy criterion 4 an approach combining a probabilistic propagation of uncertainty, a sensitivity analysis and a set of disaggregated sub-models is used.

The proposed methodology is illustrated in Figure 1. At first, boundary conditions and assumptions are defined. Next, a dataset is created with country statistics and technical data collected from available literature. Subsequently, a preliminary theoretical potential is stochastically calculated for each biomass category using a Monte Carlo algorithm. This algorithm calculates a preliminary uncertainty and performs a sensitivity analysis to identify key contributors to the uncertainty. Then, estimation of key contributors is improved by making a more thorough search of literature and by disaggregating variables into sub-models.

Thereupon, the final theoretical potential is stochastically calculated and the uncertainty is quantified. Results from the theoretical potential are then used to stochastically calculate a preliminary technical potential. Key variables are subsequently identified and improved using the same technique described above. Then, the final technical potential is recalculated. Finally, results from existing studies are re-evaluated using the proposed calculation method and the published assumptions (see Annex 1 in Ref. [5]) and compared to present results.

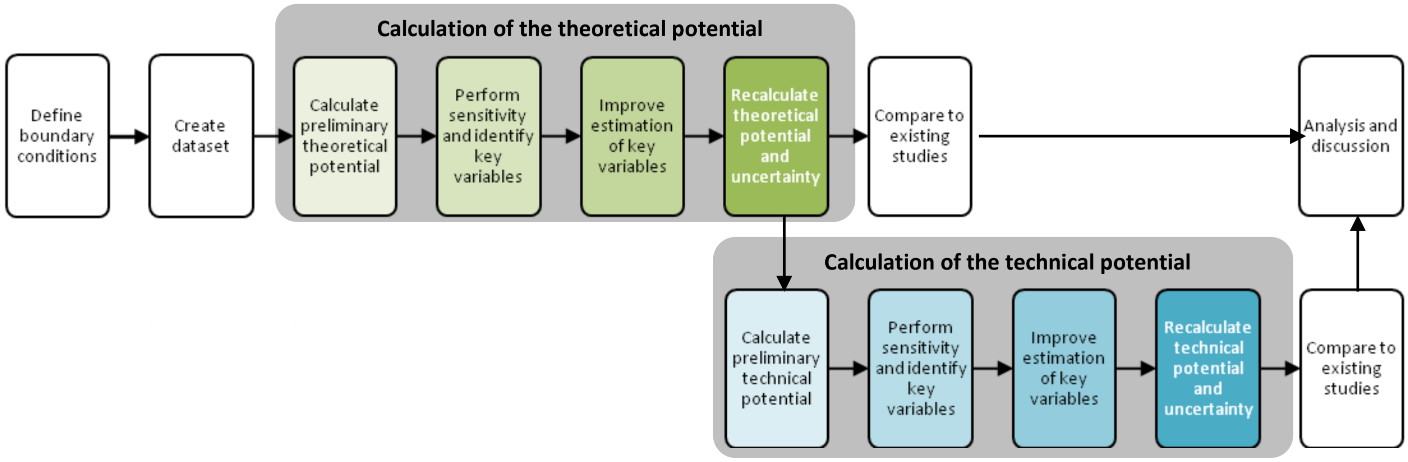

Figure 1 Methodology to estimate the biomass energy potential

3.1 Boundary conditions and assumptions

According to Spiegelhalter and Riesch [12], the choice of the model structure, boundaries and assumptions is a pragmatic compromise between the credibility of results and the effort to create and analyze the model. Thus, it is proposed to clearly define biomass categories based on the guidelines suggested by Rosillo-Calle et al. [13] and Slade et al. [14]. The proposed definition should be regarded as general and should be used with caution as there is not a universally accepted definition. More site-specific sub-categories and boundaries can be determined for different countries or regions as needed. Firstly, biomass energy potential is defined as the amount of energy contained in biomass. Bioenergy potential is defined as the energy associated to secondary energy resources/carriers such as electricity and biofuels after conversion losses [14]. This methodology focuses only on the biomass energy potential. The biomass is further divided into terrestrial biomass and non-terrestrial biomass (e.g. algal biomass). This methodology focuses only on terrestrial biomass. Terrestrial biomass is classified into woody and non-woody biomass. Woody biomass comprises various sub-categories including natural forest and woodlands, forest plantations and energy plantations. On the other hand, non-woody biomass comprises sub-categories including agricultural crops, animal waste and urban waste. Under each of these sub-categories biomass is produced either for energy or non-energy purposes. Non-energy uses of biomass include supply for food and fiber as well as feedstock to the industrial sector. Current energy utilization is further divided into two categories: traditional use (wood fuel for cooking and heating) and modern use (use of bagasse and residues for heating, power generation and combined heat and power (CHP), biofuel production, etc.). Four main biomass categories are considered:

- Forestry and wood industry: wood fuel, forestry residues and industrial residual wood.
- Agricultural residues: residues from agro-industry (e.g. bagasse) and crop residues (e.g. rice husk, cotton husk, etc.).
- Animal waste: manure from cattle, poultry, pork, etc.
- Urban waste: municipal solid waste producing landfill gas, residues from the wholesale market, demolition residues, residual methane from water treatment plants, pruning residues, etc.

The energy potential associated to biofuels is excluded to avoid potential confusion between primary energy resources (e.g. residues and wastes) and secondary energy resources/carriers (e.g. biofuels). In this sense and as discussed above, the present definition refers only to the biomass energy potential. For the category of animal waste, it is assumed that the energy potential derives from biogas produced from manure through a bio-digestion process [15]. Two levels of biomass energy potential are evaluated, the theoretical potential and the technical potential. The theoretical potential is defined as the maximum amount of biomass that can be used for energy purposes, explicitly excluding biomass used for food, fiber (e.g. round wood) and feedstock for the industry (e.g. co-products). The technical potential is defined as the fraction of the theoretical potential that is available for energy production at current conditions and constraints, after considering current energy utilization and competition with other uses and various constraints. Acknowledged limitations of the proposed system boundaries include:

- It does not include the energy potential associated with the use of idle crop land and other uncultivated land.
- It does not include the potential for producing biofuels from primary biomass energy resources.
- It does not include the potential for producing secondary energy resources/carriers (e.g. electricity, heat, etc.) from primary biomass energy resources.

3.2 Mathematical formulation

This section presents the mathematical formulation of the methodology to calculate the theoretical and technical biomass energy potentials. The overall theoretical biomass energy potential is estimated as the sum of potential associated with each biomass category, see (1). Similarly, the technical biomass energy potential is calculated by using (2).

$$Q = Q_{AR} + Q_{AW} + Q_F + Q_U \quad (1)$$

$$Q^T = Q^T_{AR} + Q^T_{AW} + Q^T_F + Q^T_U \quad (2)$$

The energy potential associated with agricultural residues is calculated using the crop production P_i, by-product to crop ratio $k_{i,j}$, moisture content $M_{i,j}$ and the lower heating value $LHV_{i,j}$, as shown in (3) and (4).

$$Q_{AR} = \sum_i \sum_j P_i \cdot k_{i,j} \cdot (1 - M_{i,j}) \bullet LHV_{i,j} \quad (3)$$

$$Q^T_{AR} = \sum_i \sum_j P_i \cdot k_{i,j} \cdot (1 - M_{i,j}) \bullet LHV_{i,j} \cdot a_{i,j} \quad (4)$$

The energy potential of animal waste is calculated from the amount of biogas produced from manure from the different type of animals (*m* is the type of animal, for instance pigs, chicken, cows and horse, whereas *n* is the sub-type of animal for instance young, boar and sow for pigs) through a bio-digestion process:

$$Q_{AW} = \sum_m \sum_n H_{m,n} \cdot f_{m,n} \cdot b_{m,n} \bullet LHV_{m,n} \quad (5)$$

$$Q^T_{AW} = \sum_m \sum_n H_{m,n} \cdot f_{m,n} \cdot b_{m,n} \bullet LHV_{m,n} \cdot a_{m,n} \quad (6)$$

The energy potential of the category of forestry and wood industry is calculated using the equations (7) and (8). In these equations P_r represents the production of the r-th forestry resource (e.g. wood fuel, round wood, etc.), c_r represents the by-product to product ratio in forestry, ρ_r symbolizes the density (t/m^3, dry basis) and LHV_r the lower heating value.

$$Q_F = \sum_r P_r \cdot c_r \cdot \rho_r \cdot LHV_r \quad (7)$$

$$Q^T_F = \sum_r P_r \cdot c_r \cdot \rho_r \cdot LHV_r \bullet a_r \quad (8)$$

Finally, for the urban waste category the energy potential is calculated using (9) and (10) by multiplying the production volume of each urban waste type P_x by the lower heating value LHV_x.

$$Q_U = \sum_x P_x \cdot LHV_x \quad (9)$$

$$Q^T_U = \sum_x P_x \cdot LHV_x \bullet a_x \quad (10)$$

3.3 Uncertainty analysis

The ability of mathematical models to describe reality is limited by various uncertainties, including unpredictability of future events, limited knowledge about the model structure, limited availability of accurate data, indeterminacy and ignorance [12]. In the particular case of biomass production, the scale of uncertainty and ignorance is very large [16]. This problem complicates even further in developing countries where data and analyses are scarcer. Thus, following the suggestions of Spiegelhalter and Riesch [12], Johnson et al [17] and Roos and Rakos [18], an approach to address uncertainty related to biomass energy potential is proposed in this paper (see Figure 2). This approach is an attempt to find a balance between simplicity and realism, avoid overly complex models that tend to lose credibility and acknowledge that there are factors that cannot be mathematically represented in models. Key features are summarized below:

- Limited knowledge about the model structure: while the model structure presented in section 3.2 is acknowledged in scientific literature [13], [19], [20], [21], there are alternative methods to quantify the biomass production and its associated energy potential. Examples include: a) top-down demand-driven methods to estimate the biomass energy potential based on supply curves, b) the use of agriculture residue yields (kg/ha) which can be measured or estimated as a function of crop yields [22] and c) the use of higher heating value (HHV) [14], [23], [24]. No particular technique to quantify this uncertainty is proposed, but rather it is acknowledged that difference in results might arise by selecting alternative accounting methods.

- Limited availability of accurate data: there is uncertainty related to data availability and its quality, data variability, randomness, systematic error and to the unsuitability of some parameters to be mathematically described [17]. It is proposed to employ a stochastic simulation featuring a detailed probability function for parameters with sufficient available data and an extended uniform distribution (EUD) for those parameters with limited available information. As described by Goulet and Smith, the extended uniform distribution is a simple technique to describe errors in absence of more precise information [25], [26]. It is a probability density function that by considering multiple orders of uncertainty contributes to increase the robustness of models. A more detailed description of EUD distributions and their set-up is shown elsewhere [25]-[27]. In this paper a EUD distribution with two orders of uncertainty and a width factor $\beta = 0.3$ is used. On the other hand, a more comprehensive search of literature certainly might help to reduce the uncertainty associated to a parameter. However, performing a thorough literature search for all the variables of very complex system might be challenging and non-practical when the number of variables is large. It is thus proposed to perform: a) a sensitivity analysis to identify key parameters (by using a Monte Carlo algorithm), b) a thorough search of literature for key parameters and c) a recalculation of uncertainty of model outputs with improved parameters.

- Indeterminacy and ignorance: there are four main known model limitations: 1) there might be unknown correlations of model parameters, 2) the model does not improve the estimation of non-key parameters, 3) the methodology does not include idle land to estimate the biomass energy potential and 4) the methodology does not consider biomass for final human usage to estimate the biomass energy potential. Limitations #1-#3 are considered of moderate quality according to the GRADE scale [12], for which further research is likely to have an important impact on the confidence in the estimate and may change the estimate itself. Limitation #4 is considered of high quality, for which further research is very unlikely to change confidence in the estimate and may change the estimate.

- Unpredictability of future events: there are some events that cause uncertainty in the estimation of the technical biomass energy potential. To address this uncertainty, a scenario analysis is highly recommended. However, for the sake of brevity, a scenario analysis is not included in this paper.

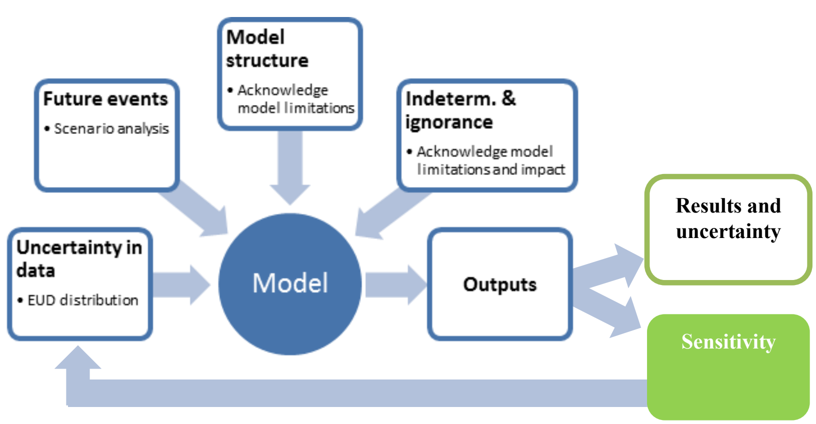

Figure 2 Approach to address uncertainty

4. STUDY CASE: COLOMBIA

The methodology to estimate the biomass energy potential and its associated uncertainty when quality and availability of data are limited is applied to a case study of Colombia. Similarly to other developing countries, Colombia has an obvious interest on biomass: biomass is the second largest renewable energy resource after large hydro. In 2009, biomass contributed to 67% (3.4 PJ, excluding large hydro) of the renewably generated electricity, to 4.2% (15.7 PJ) of the energy supply in the transport sector and to 3.9% (193.5 PJ) of the overall primary energy supply (4.93 EJ according to UPME) [28]. Earlier studies indicate that nearly half of the country's available biomass energy potential remains untapped.

4.1 Prior art

Five studies estimating the current biomass energy potential in Colombia are available in literature, i.e. UPME [28], AENE [29], Escalante et al. [30], Arias et al. [31] and Kline et al. [32]. The Mining and Energy Planning Unit (UPME), an affiliate of the Ministry of Mines and Energy, has been particularly active in the process of assessing the biomass energy potential. Actually, UPME has developed one biomass energy estimation [28] and has participated in and sponsored two additional studies [29], [30]. Independent estimations have been created by foreign institutions or project consortiums, examples include the reports from the Oak Ridge National Laboratory [32] and the collaborative European-Latin American project consortium BioTop [31]. A comparative overview of the year of estimation, considered biomass categories, type of potential, type of approach and type of methodology for the different studies is presented in Table 1 1. In general, all estimations have been published in the last five years except the AENE report, which was released in 2003. All studies have estimated the theoretical biomass energy potential while only three reports also evaluated the technical potential. Across studies, five biomass categories are considered relevant to Colombia: agricultural residues, animal waste, forestry and wood industry, biofuels and urban waste. Although biofuels are secondary energy carriers derived from biomass resources, in some of these studies they are indistinctly treated compared to primary biomass energy resources (residues, wastes, etc.). While most studies evaluated the energy potential of at least three of these categories, the entire energy potential of all biomass categories has not been reported. Uncertainty in predictions has not been reported in any of the assessments. Regarding the theoretical potential of the forestry and wood industry, most of the studies evaluated the residual biomass associated to the production of round wood. However, the biomass potential evaluated using above-ground biomass in forests has not been reported.

The preferred methodology throughout studies is the resource-focused approach employing statistical analysis. This methodology has been employed in four reports and it has been notably combined with a spatially explicit analysis to offer regional results in Escalante et al [30]. The methodology used by UPME has not been reported. Generally speaking, the approach employed in all existing studies is characterized by a three steps process to estimate the biomass energy potential:

1. Use available statistics to define production volumes and yields of primary agricultural and forestry biomass resources including dedicated crops, energy crops, animal production and forestry and wood industry.

2. Use available statistics to define production volumes (i.e. by using by-product to product ratios) and the heating value of by-products associated with primary biomass resources. At this step the theoretical biomass energy potential for each biomass category is estimated by multiplying the heating value by the production volume. With exception of the AENE report, all other reports estimated the theoretical energy potential of biomass on a dry matter basis.

3. Assume or estimate an availability factor for the primary biomass resources and the associated by-products to produce energy. At this step the technical biomass energy potential for each biomass category is estimated by multiplying the theoretical potential with a corresponding availability factor.

Although similar approaches are used across studies, non-reported methodologies, omissions and inconsistencies in assumptions and data are found. In order to allow a meaningful comparison of results in further sections, a comparative summary of assumptions taken by different studies is presented in Annex 1 in Ref. [5].

4.2 Site-specific boundary conditions and assumptions

The boundary conditions and assumptions defined in section 3.1 are applied to the specific case of Colombia, see Figure 3. Non-energy uses of biomass (yellow area in Figure 3) include supply for food and fiber as well as feedstock to the industrial sector. Current biomass energy utilization in Colombia (blue area in Figure 3) is divided into two categories: traditional use (wood fuel for cooking and heating) and modern use (use of bagasse and palm oil residues for heating, power generation and combined heat and power (CHP)). Four main biomass categories are considered: forestry and wood industry, agricultural residues, animal waste and urban waste.

Table 1 Comparative overview of existing estimations of biomass energy in Colombia

Study	Year of publication and estimation	Potential	Approach	Methodology	Considered biomass categories: Agricultural residues	Biofuels	Animal waste	Forestry & wood industry	Urban waste
UPME [28]	2011/2009	Theoretical	Resource-focused	Not reported	✓	✓	×	✓	×
AENE [29]	2003/2003	Theoretical & technical	Resource-focused	Statistical analysis	✓	✓	×	✓	×
Escalante et al. [30]	2011/2010	Theoretical	Resource-focused	Statistical analysis and spatially explicit analysis	✓	×	✓	×	✓
Arias et al. [31]	2009/2008	Theoretical & technical	Resource-focused	Statistical analysis	✓	✓	✓	✓	×
Kline et al. [32]	2008/2007	Theoretical & technical	Resource-focused	Statistical analysis	✓	✓	×	✓	×

The energy potential associated to biofuels is excluded to avoid potential confusion between primary energy resources (e.g. residues and wastes) and secondary energy resources/carriers (e.g. biofuels). Two levels of biomass energy potential are evaluated, the theoretical potential (green area in Figure 3) and the technical potential (grey area in Figure 3). Nearly half of the land in Colombia is covered with forests (58.6 million ha), from which 16% are protected areas and about 70-75% are tropical forests with high biodiversity and carbon pools [33], [34]. The theoretical biomass energy potential is evaluated at two scales: a) one including the entire above-ground biomass in forests but excluding protected areas and b) one including only the biomass associated to the production of round wood. The first case is estimated only for comparative purposes, as from a sustainability and ecological point of view the use of biomass from tropical forests is prohibitive. The second case is considered more attainable and further used to calculate the technical biomass energy potential.

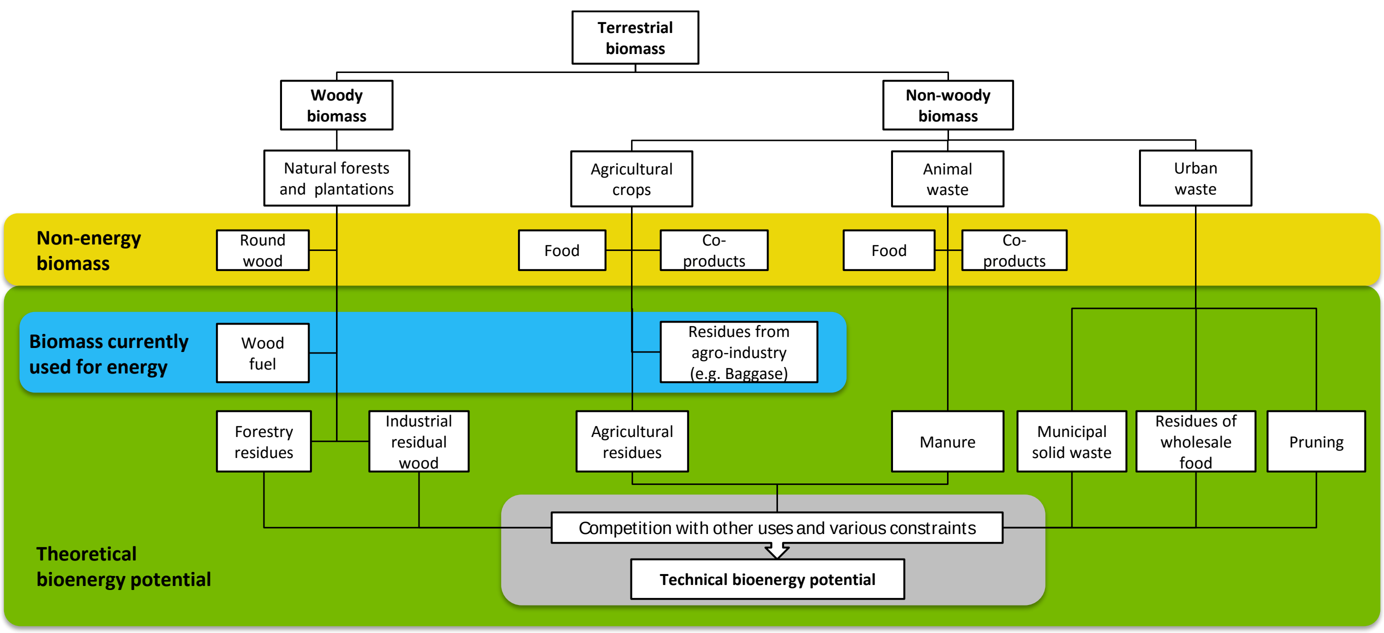

Figure 3 Boundary conditions for Colombia

4.3 Calculation of the theoretical potential

Country statistics and technical data are collected from available literature. Given heterogeneity of data found in literature, a priority order between different sources of information is set. As suggested by Arias et al. [31], first priority is given to official statistics from the government, second priority to data provided by international agencies and third priority to scientific papers. While country statistics are generally available, site-specific technical data associated to biomass resources in Colombia was not always readily accessible. For this reason, some of the references used to create a dataset correspond to countries other than Colombia. A criterion proposed by Thompson [35] for rejecting outlying observations is used to filter and exclude suspiciously high or low values found in literature.

The dataset for agricultural residues is shown in Table 2. The production volumes of agricultural crops is taken from the Ministry of Agriculture and Rural Development [36], which in turn estimate it through a survey based on a multiple-frame sampling method described in the National Agriculture Surveys [37]-[39], [40]. This method combines a two stages area-frame sampling with a list-frame sampling to estimate production volumes of the samples and through statistical methods infer the production volumes of the entire population [37]-[39], [40]. The method involves a sample error (i.e. a coefficient of variability) associated to the degree of approximation, which according to the National Administrative Department of Statistics (DANE) is normally distributed [37]-[39], [40]. It is found that the National Agriculture Survey of 2010 does not include the coefficient of variability of various crops and therefore has been used the survey of 2009 that includes data for most crops [40]. Unfortunately, this survey does not report data for cotton, cane (large-scale) and palm oil. For these crops data is scarce and some assumptions have to be taken. For cotton, the coefficient of variability reported in the National Agriculture Survey of 2000 [38] is used, for palm oil the coefficient of variability reported in the survey of 1997 [39] is used and for cane (large-scale) the uncertainty in measuring bagasse reported by a typical sugar mill with cogeneration under a CDM project [41] is used. The probability distributions used are normal for the production volumes of crops and EUD for the by-product to crop ratio, moisture content and lower heating value.

The dataset for animal waste is shown in Table 3. The inventory of cattle, swine, poultry and equine is taken from the Ministry of Agriculture and Rural Development [36], which in turn estimates it through the National Agriculture Surveys [37]-[39], [40]. According to the National Administrative Department of Statistics (DANE), the sample error in inventorying animals is also normally distributed [37]-[39], [40]. To be consistent with the assumptions made for agricultural residues, the normally distributed coefficient of variability associated to each of the animal types is taken from the National Agriculture Survey of 2009 [40]. Data on biogas yield from manure is available for the different animal types but is not disaggregated by animal sub-type (i.e. young, boar and sow for pigs). Therefore, the biogas yield from manure for each animal type is assumed to remain constant for the different animal sub-types. The lower heating value of biogas is not commonly reported and instead the ranges of chemical components (e.g. CH_4, CO_2) of biogas from manure are published. However, these ranges are not disaggregated by animal type and sub-type. Therefore, it is assumed that the lower heating value (MJ/m^3) of biogas is the same for all animal types and subtypes. It is calculated using Aspen Hysys® at 1 bar and 15°C, based on the biogas composition reported in [42] and [43]. The probability distributions used are normal for the inventory of animals and EUD for the manure production per head, the biogas yield from manure and the lower heating value.

The dataset for forestry resources is shown in Table 4. As mentioned above the theoretical biomass energy potential is evaluated at two scales: a) including the entire above-ground biomass in forests but excluding protected areas and b) including only the biomass associated to the production of round wood. The volumes of wood fuel, round wood and industrial round wood are taken from FAOSTAT [44]. FAOSTAT does not report the sampling error and therefore some assumptions are taken. It is assumed that the sampling error is equal to that of the current land used for forestry in Colombia, which is available in the National Agriculture Survey of 2009 [40]. It is found that the density of wood fuel varies widely depending on the species. Thus, 60 different species of trees producing wood in Colombia are identified based on data from AENE [35] and the corresponding density per specie is taken from IPCC [45]. Nevertheless, this density varies widely from 0.33 to 0.87 dry ton per cubic meter. Density of forest field residues was not found in the literature. Therefore, it is assumed that density of forest field residues is equal to the density of wood fuel. Similarly, the lower heating value of industrial residual wood is assumed to be equal to that of forest field residues. The probability distributions used are normal for the production of forestry resources (i.e. wood fuel, round wood, etc.) and EUD for the density, the by-product to product ratio and the lower heating value.

Data for above-ground biomass is also shown in Table 4. The estimation of overall above-ground biomass found in forests in Colombia is taken from the national inventory of carbon reserves in forests in Colombia by IDEAM [33], while the estimation only for protected forests is taken from UAESPNN [34]. The IDEAM study reports for each forest type the area (ha), the biomass yield (dry t/ha) and a normally distributed standard deviation. Similarly, the UAESPNN study reports for each forest type the size of the protected area (ha) and the biomass yield (dry t/ha). However, this study does not report the variability in biomass yield, therefore some assumptions are taken. It is assumed that the coefficient of variability of the biomass yield in protected areas is equal to that of forest areas published by IDEAM [33]. It is also assumed that the uncertainty associated to the size of protected areas (ha) can be represented by the sampling error associated to the current land used for forestry in Colombia [40]. Then, the uncertainty of the biomass produced in protected areas is estimated using a model in Oracle® Crystal Ball 11.1.2.1. The biomass produced in forests in Colombia excluding protected areas is calculated and shown in Table 4. From this biomass two products are produced: round wood and forestry residues. The production fractions for each one are calculated using the data shown in Table 4, e.g. the fraction of forestry residues per unit of round wood. The probability distributions used are normal for the biomass produced in forests in Colombia excluding protected areas, and EUD for the density, the by-product to product ratio and the lower heating value.

Finally, the dataset for urban waste is shown in Table 5. The range of production of municipal solid waste (MSW) per capita is taken from various reports published by the Colombian Administration of Public Services (Superservicios) [46]-[48]. This data is multiplied by the country population in 2010 (taken from the National Administrative Department of Statistics (DANE) [49]), to obtain the overall production volume of MSW. Subsequently, the MSW volume is used as an input in the Colombia Landfill Gas Model Version 1.0 [50] to estimate the amount of landfill gas that can be generated in landfill applications. The model calculates landfill gas generation by using a first order decay equation, specific data of climate, waste composition and disposal practices in each of the 33 departments in Colombia. It is assumed that (i) the type of landfill is engineered or sanitary, (ii) the start year of the landfill is 2005[1] and (iii) the projected closure year is 2030. The lower heating value of the landfill gas is estimated using Aspen Hysys® at 1 bar and 15°C, based on the ranges of its chemical components available in literature [43], [51], [52]. The production volumes of residues from wholesale food market and pruning are only available in one reference, i.e. Escalante et al. [30]. Based on a personal communication with experts on waste disposal in Colombia, it was assumed that these production volumes might vary within a range of ±15% similarly to the variability of MSW production. EUD distributions are used for all the variables related to urban waste.

4.3.1 Preliminary calculation of the theoretical biomass energy potential

The theoretical biomass energy potential is calculated using the methodology described in section 3 and the datasets shown in Table 2 – Table 5 as inputs. The uncertainty calculation and sensitivity analysis in this investigation are conducted in Oracle® Crystal Ball 11.1.2.1 using 50000 trials and a Latin Hypercube sampling method using 1000 bins. Results for the theoretical potential including and excluding above-ground biomass in forests are shown in Table 6. As mentioned before, the results for the theoretical potential including the above-ground biomass are shown only for comparative purposes. Results for theoretical potential including the above-ground biomass show the vast potential (220 EJ) of forestry resources in the country. However, most of this potential is associated to tropical forests, which is prohibitive from a sustainability and ecological point of view. There is a large uncertainty in this estimation (±46%), partly as a result of a considerable uncertainty in the prediction of the above-ground biomass in forests in the country (±23%). In comparison, the theoretical potential including only the forestry resources associated to the current wood exploitation is three orders of magnitude lower (0.75 EJ) and with a lower associated uncertainty (±19%). The theoretical potential excluding above-ground biomass is considered more attainable and is further used to calculate the technical biomass energy potential. The categories that contribute the most to this theoretical potential include agricultural residues with 52.8%, forestry residues with 25.2% and animal waste with 20.6%. Contribution from urban waste is marginal and accounts for 1.3% of the theoretical potential. A sensitivity analysis using the propagation of uncertainty is performed to the preliminary theoretical potential and results are shown in Figure 4. Results indicate that in a model of 116 variables, 11 contribute to nearly 90% of the uncertainty: the density of wood fuel (44%), the by-product to product ratio of forestry residues (13%), the LHV of biogas from manure (6%), the moisture of cane leaves and tops (6% for large-scale and 5% for small-scale), the biogas yield from cattle manure (6%), the manure production for cattle > 36 months (5%), the by-product to product ratio for cane leaves and tops (2% for large-scale and 1% for small-scale) and finally the LHV for wood fuel (2%) and cane leaves and tops (1%). These variables can be grouped into parameters describing: a) forestry residues (density, by-product to product ratio and LHV), b) cattle manure (LHV, biogas yield, manure production) and c) cane leaves and tops (moisture, by-product to product ratio and LHV). A more thorough search of literature is performed for these groups of variables aiming at improving their estimation and reducing the associated uncertainty. The procedure to improve the estimation of key parameters is not shown in this paper for the sake of brevity.

4.3.2 Improved calculation of the theoretical biomass energy potential

The theoretical potential is recalculated using the improved estimation of key parameters. Results are then compared to the preliminary estimation and shown in Figure 5. It can be observed that while both estimations have an almost identical mean, the uncertainty associated to the recalculated estimation is significantly lower. In fact, the preliminary calculation estimates a theoretical potential of 0.748 EJ with a C.I. of -17.0%, 19.3% (slightly positively skewed), while the improved evaluation estimates a theoretical potential of 0.744 EJ with a C.I. of -7.2%, 7.8%. A particular reduction in uncertainty is obtained for the categories of forestry, animal waste and agricultural residues. Results also show the effectiveness of the sensitivity analysis followed by an improved estimation of key parameters.

[1] Resolution 1045 and 1390 from Ministry of Environment, Housing and Territorial Development forbid the use of unmanaged waste disposal sites in Colombia as of 2005.

Table 2 Dataset for agricultural residues in 2010

Crops	P_i (t, w)[2]	$\frac{\sigma_{P_i}}{P_i}$	Residue	$k_{i,j}$				$M_{i,j}$				$LHV_{i,j}$ (kJ/kg, d)			
				Min	Max	N	References	Min	Max	N	References	Min	Max	N	Ref.
Cotton	103257	0.117[3]	Husk	1.77	2.76	3	[29][53][54]	0.07	0.10	3	[61]	14790	17492	5	[61][62]
Palm Oil	5367541[4]	0.050[5]	Stone	0.06	0.17	5	[30][53]-[55]	0.07	0.10	5	[61][53][54]	16483	20020	3	[30][61]
			Fiber	0.14	0.22	5	[30][53]-[55]	0.31	0.36	3	[30][61]	17856	17882	2	[30][61]
			Rachis[6]	0.23	0.50	5	[29][30][53]-[55]	0.50	0.58	5	[29]-[31][53][54]	16824	18502	2	[30][61]
Cane (large-scale)	20060074[7]	0.030[8]	Leaves & top	0.25	0.47	5	[29][30][32][53][54]	0.30	0.75	5	[29]-[31][53]	14800	21429	4	[29][30][54][61]
			Bagasse	0.28	0.39	7	[29]-[32][53][54][56]	0.41	0.52	5	[29]-[31][62]	16240	18644	8	[29][30][61][62]
Cane (small-scale)	16797074[5]	0.066[9]	Bagasse	0.28	0.34	6	[29][31][32][53][54][56]	0.41	0.52	5[10]	[29]-[31][62]	16240	18644	8[8]	[29][30][61][62]
			Leaves & top	0.25	0.46	5	[29][30][32][53][54][56]	0.30	0.75	5[8]	[29]-[31][53]	14800	21429	4[8]	[29][30][61][62]
Coffee	779137[11]	0.034[7]	Pulp	2.10	2.67	4	[30][54][57][58]	0.60	0.80	4	[29][30][61][63]	15880	17820	2	[30][58]
			Husk	0.21	0.23	3	[30][54][57]	0.07	0.12	4	[30][61][63]	13611	18535	5	[30][58][61][66]
			Stem	3.02	3.33	2	[30][58]	0.14	0.26	2	[30][63]	18343	19750	2	[30][58]
Corn	1099512	0.072[7]	Stem & leaves	0.93	2.00	3	[30][53]	0.15	0.15	2	[53][54]	14347	16520	4	[30][61][62]
			Cob	0.27	0.27	3	[30][53][54]	0.16	0.27	2	[30][31]	14184	17580	3	[30][54][62]
			Skin	0.20	0.21	3	[30][53][54]	0.05	0.09	3	[30][61]	15962	17690	3	[30][67]
Rice	2449776[12]	0.044[7]	Stem	1.76	2.35	4	[30][53][54]	0.73	0.88	3	[30][61]	13025	15340	3	[30][61][62]
			Husk	0.20	0.27	4	[29][30][53][54]	0.04	0.14	6	[29][30][53][54][61]	13760	17818	7	[29][30][61][62]
Banana	2016992	0.102[7]	Rachis	1.00	1.08	2	[30][59]	0.94	0.94	2	[30][64]	7569	15530	2	[30][59]
			Stem	3.00	6.51	3	[30][60]	0.92	0.94	3	[30][64][65]	8502	16130	5	[30][59][60][64][68]
			Rejected fruit	0.15	0.67	3	[30][59]	0.79	0.83	2	[30][64]	10410	15748	2	[30][64]
Plantain	2970435	0.048[7]	Rachis	1.00	1.08	2[13]	[30][59]	0.94	0.94	2[11]	[30][64]	7565	15530	2[11]	[30][59]
			Stem	3.00	6.51	3[11]	[30][60]	0.92	0.94	3[11]	[30][64][65]	8502	16130	5[11]	[30][59][60][64][68]
			Rejected fruit	0.15	0.67	3[11]	[30][59]	0.79	0.83	2[11]	[30][64]	10410	15748	2[11]	[30][64]

[2] Ministerio de Agricultura y Desarrollo Rural [36].
[3] Encuesta Nacional Agropecuaria 2000 [38].
[4] Fresh fruit bunch (FFB).
[5] Encuesta Nacional Agropecuaria 1997 [39].
[6] Also known as Empty fruit bunches (EFB).
[7] Cane stalk excluding leaves and tops.
[8] UNFCCC, CDM form for submission of request for deviation [41].
[9] Encuesta Nacional Agropecuaria 2009 [40].
[10] Assumed to be the same than for large-scale sugar cane.
[11] Green coffee bean (unroasted).
[12] Paddy rice (unmilled).
[13] Assumed to be the same than for banana.

Table 3 Dataset for animal waste and forestry in 2010

Type	Subtype	$H_{m,n}$ (heads)[14]	$\frac{\sigma_{w_{m,n}}}{H_{m,n}}$ [15]	$f_{m,n}$ (t/head, w)				$b_{m,n}$ (m^3/t, w)[16]				$LHV_{m,n}$ (MJ/m^3)[17]			
				Min	Max	N	References	Min	Max	N	References	Min	Max	N	References
Cattle	<12 months	5377345	0.023	1.46	1.49	2	[30][69]	23	40	4	[15][31][42]	16.99	25.46	4	[42][43]
	12-24 months	6277827	0.023	3.29	4.30	3	[30][69]								
	24-36 months	6526156	0.023	3.48	5.11	3	[30][69]								
	> 36 months	9572673	0.023	6.57	15.23	10	[30][31][69][42]								
Swine	Nursey	633895	0.028	0.10	0.22	2	[30][69]	40	70	4	[15][31][42]				
	Grow	1426360	0.028	0.38	0.45	3	[30][69][70]								
	Grow-finish	1609263	0.028	0.70	0.80	3	[30][42][70]								
	Boar	39397	0.028	1.19	2.05	5	[30][31][69][70]								
	Lactating sow	314392	0.028	2.69	5.46	3	[30][69][70]								
	Gestating	76691	0.028	1.24	1.97	4	[30][31][69][70]								
Poultry	Meat	571000000	0.067	0.02	0.03	3	[30][31][69]	55	91	3	[15][31][42]				
	Eggs	30049000	0.067	0.04	0.04	3	[30][31][69]								
Equine		2505580	0.054	7.45	9.22	3	[31][69]	32	48	3	[15][31][42]				

[14] Ministerio de Agricultura y Desarrollo Rural [36].
[15] Encuesta Nacional Agropecuaria 2009 [40].
[16] A same biogas yield from manure (m^3/t, w) is assumed for all cattle subtypes, swine subtypes and poultry subtypes.
[17] The same lower heating value (MJ/m^3) of biogas is assumed for all animal types and subtypes. It is calculated using Aspen Hysys® at 1 bar and 15°C, based on the composition reported in [42][43].

Table 4 Dataset for forestry resources in 2010

Category	Sub-category	P_r ([a] m³, [b] t,d)	$\frac{\sigma_{P_r}}{P_r}$ [18]	Product, residue	c_r				ρ_r (t/m³, d)				LHV_r (kJ/kg, d)			
					Min	Max	N	References	Min	Max	N	References	Min	Max	N	References
Forestry & wood industry	Wood fuel[a]	8826000[19]	0.035	-					0.33	0.87	60[20]	[29][45]	16734	19384	8	[13][29][61][62]
	Total round wood[a]	11216000[19]	0.035	Forestry residues	0.30	1.00	17	[13][29][31][32][53]	0.33	0.87	60[21]	[29][45]	16791	20768	9	[13][29][61][62]
	Industrial round wood[a]	2390000[19]	0.035	Ind. residual wood	0.30	0.55	19	[29][31][71]	0.39	0.75	21	[29][31][32][53][71]	16791	20768	9[22]	[13][29][61][62]
Above-ground biomass	Above-ground biomass[b]	14289723630[23]	0.1910[24]	-												
	Biomass in protected forest[b]	2321106032[25]	0.1950[26]	-												
	Biomass excl. protected forest[b]	11968617598	0.2315[27]	Round wood[28]	0.500	0.769	17	[13][29][31][32][53]	0.33	0.87	60	[29][45]	16734	19384	8	[13][29][61][62]
				Forestry residues	0.230	0.5	17	[13][29][31][32][53]	0.33	0.87	60	[29][45]	16791	20768	9	[13][29][61][62]

[18] The sampling error is not available in FAOSTAT. It is assumed to be equal to the sampling error of the current land used for forestry in Colombia available in Encuesta Nacional Agropecuaria 2009 [40].
[19] Taken from FAOSTAT [44].
[20] 60 different species of trees producing wood in Colombia were taken from AENE [29], and then the corresponding density was taken from IPCC [45].
[21] It is assumed that the density of forestry residues is equal to the density of wood fuel.
[22] It is assumed that the lower heating value of industrial residual fuel is equal to that of forestry residues.
[23] Taken from the national estimation of carbon reserves in forests in Colombia [33].
[24] Calculated with areas and biomass yields from the estimation of carbon reserves in forests in Colombia [33] using Oracle® Crystal Ball 11.1.2.1.
[25] Taken from the estimation of biomass in protected forests in Colombia [34].
[26] Calculated with areas and biomass yields from estimation of biomass in protected forests in Colombia [34] using Oracle® Crystal Ball 11.1.2.1.
[27] Calculated from the above-ground biomass minus the biomass in protected forests using Oracle® Crystal Ball 11.1.2.1.
[28] Calculated based on the production ratio of forestry residues to round wood shown in Table 5.

Table 5 Dataset for urban waste in 2010

Sub-category	P_x ([a] t, w; [b] m[3])				LHV_x ([a] kJ/kg, w; [b] MJ/m[3])			
	Min	Max	N	References	Min	Max	N	References
Municipal solid waste per capita (t/inhab.)	0.1707	0.2284	6	[46]-[48]	-	-	-	-
Municipal solid waste (MSW)[29] [a]	7906667	10578147		[49]	-	-	-	-
Landfill from MSW[30] [b]	537041180	718495025		[50]	10.20	20.38	3[31]	[43][51][52]
Residues of wholesale food market[32] [a]	102179	138242	1	[30]	700	3900	5	[30][72]
Pruning[33] [a]	38089	51533	1	[30]	1627	8457	7	[30][73]

Table 6 Results of the theoretical biomass energy potential including and excluding above-ground biomass in forests

Biomass categories	Theoretical potential including above-ground biomass			Theoretical potential excluding above-ground biomass		
	Mean (EJ)	Confidence interval (95% probability)		Mean (EJ)	Confidence interval (95% probability)	
Agricultural residues	0.40	-14.9%	17.4%	0.40	-14.9%	17.4%
Animal waste	0.15	-31.1%	40.5%	0.15	-31.1%	40.5%
Forestry	219.32	-45.4%	46.3%	0.19	-48.7%	61.1%
Urban waste	0.01	-35.7%	40.4%	0.01	-35.7%	40.4%
Total	219.88	-45.5%	46.0%	0.75	-17.0%	19.3%

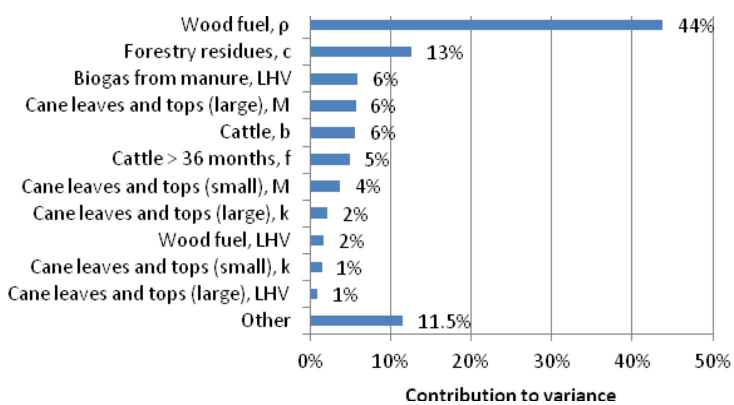

Figure 4 Sensitivity analysis for the theoretical biomass potential excluding above-ground biomass in forests

4.4 Calculation of the technical biomass energy potential

The technical biomass energy potential is calculated at current conditions and constraints following the methodology explained in section 3.2. The technical potential for each biomass category is obtained by multiplying the theoretical potential by the corresponding availability factor. The availability factor for these biomass resources is evaluated considering various constraints and excluding the fraction that is already used for energy production (heat, CHP, etc.). Firstly, the availability factors and the technical biomass energy potential are preliminarily calculated. Then, key parameters are identified through a sensitivity analysis. Subsequently, estimation of key parameters is improved through a thorough data search and disaggregated into sub-models in a similar manner as shown for the theoretical potential in section 4.3.2. Finally, the availability factors and the technical potential are recalculated.

[29] Calculated by multiplying the municipal solid waste per capita (t, w) by the total population taken from DANE [49].
[30] Calculated using the Colombia Landfill Gas Model V.1.0 [50] assuming that the type of landfill is engineered or sanitary, has started in 2005 and will be closed down in 2030.
[31] Lower heating value for landfill gas is calculated using Aspen Hysys® at 1 bar and 15°C, based on the composition reported in [43], [51] and [52].
[32] Ranges are not found in literature. After consulting experts on waste disposal, it was assumed to use the data reported by Escalante et al. [30] ± 15%.
[33] Ranges are not found in literature. After consulting experts on waste disposal, it was assumed to use the data reported by Escalante et al. [30] ± 15%.

Biomass categories	Theoretical potential (preliminary)		Theoretical potential (improved)	
	Mean (EJ)	C.I. (95%)	Mean (EJ)	C.I. (95%)
Agricultural residues	0.396	-14.9%, 17.4%	0.394	-9.0%, 9.3%
Animal waste	0.154	-31.1%, 40.5%	0.176	-14.1%, 14.6%
Forestry	0.189	-48.7%, 61.1%	0.164	-17.9%, 23.4%
Urban waste	0.010	-35.7%, 40.4%	0.010	-35.7%, 40.2%
Total	0.749	-17.0%, 19.3%	0.744	-7.3%, 7.8%

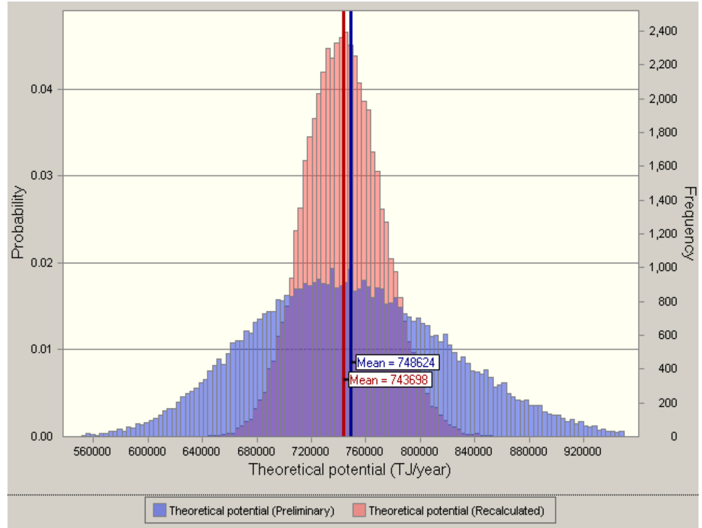

Figure 5 Preliminary vs. improved theoretical potential

4.4.1 Preliminary calculation of the technical biomass energy potential

Most agricultural residues are currently used for animal feed, soil fertilization and to provide heat (see Table 8). One special case is sugar cane at large scale, in which bagasse is used to provide heat and power to the sugar and bioethanol industry [28]. Only rachis of the palm oil tree, cane leaves and tops (large-scale) and rice husk are potentially available for energy production. The rachis or empty fruit bunch (EFB) is a solid residue from the palm oil tree resulting from the processing mills. The use of rachis varies widely by field and by region in Colombia [75]. In some fields it is completely left on the field for mulching, while in others it is partially or totally collected for various purposes (composting, burning in boilers, etc.). In the scientific literature, various studies show availability factors ranging from 0 to 100% and compare the use of rachis for mulching to replace fertilizers and for energy production [76], [77]. The availability factor of rachis is preliminarily estimated through a uniform distribution with limits between 0-100%. About 70% of the cane fields in Colombia are currently burned before harvesting to facilitate the collection of stalks [75]. After harvesting, the remaining burned residues (leaves, tops, etc.) are left on the field for soil replenishment, while stalks are transported to the mill. If cane would be unburned, part of the cane leaves and tops might be available for energy production. In the literature, availability factors accounting for the fraction of residues that should be left on field range from 0-50% [74], [75], [78]. Thus, the preliminary availability factor for cane leaves and tops is described by a EUD distribution using 0-50% as limits. Rice husk is currently used as fertilizer in the flower industry and as a feedstock in poultry sheds. AENE reports that only large mills producing more than 100 tons of husks daily can afford the costs of exploiting rice husk for energy production [29]. 44% of the production of husk corresponds to mills with these characteristics. Therefore, the preliminary availability factor for rice husk is described as a EUD distribution using 0-44% as limits.

In the category of animal waste, manure from poultry is currently used as fertilizer in agricultural crops and is not expected to be available in the short-term. Manure from equine is currently wasted but it is not expected to become available for energy generation given its decentralized production. Manure from cattle and pork is currently wasted and might be potentially used for energy purposes [30], [31]. Data on availability of manure from cattle or pork in Colombia is scarce. As a preliminary estimation, EUD distributions are created using the limits shown by authors in Ref. [5]. The preliminary availability factor for manure from cattle is described by a EUD distribution using 11.7-23.5% as limits, while for manure from pork another EUD distribution uses 7-14.5% as limits.

In the category of forestry and wood industry, significant availability is expected from forestry residues. Forestry residues are currently left for soil replenishment or simply as waste [29], whereas industrial residual wood is a marketable by-product not currently available. Availability factor for forestry residues range in the literature from 0% to 50% [29], [31], [32]. Therefore, the preliminary availability factor for forestry residues is described by a EUD distribution using 0-50% as limits.

In the category of urban waste, residues from pruning and from wholesale food market are currently used for animal feed and are not considered available. Landfill gas is currently produced in waste disposal sites and either flared or vented. The availability of landfill gas depends mainly on technical characteristics of the landfill site, including site management practices, collection system coverage, waste depth, cover type and extend, landfill liner, etc. [50]. SCS Engineers estimate that collectability of landfill gas range between 0.5-0.9. Thus, the technical constraint factor is described by a EUD distribution using 0.5-0.9 as limits.

The preliminary biomass energy technical potential is then calculated in Oracle® Crystal Ball 11.1.2.1 using 50000 trials and a Latin Hypercube sampling methods using 1000 bins. Results of the preliminary estimation of the technical biomass energy potential and its associated sensitivity analysis are shown in Table 7. The preliminary technical potential amounts to 78607 TJ with an uncertainty of -36%, +39% which is significantly high. Results of the sensitivity analysis by propagation of uncertainty show that four parameters account for 85% of the overall uncertainty. The four parameters are the availability of forestry residues (43%), availability of cane leaves and tops (25%), availability of rachis (9%) and availability of cattle manure (9%). In order to better estimate these parameters, a more thorough search of literature is combined with the development of more detailed sub-models. As made for the theoretical potential estimation, the procedure to improve the estimation of key parameters is not shown in this paper for the sake of brevity.

Table 7 Preliminary technical biomass energy potential and associated sensitivity analysis

Biomass categories	Preliminary technical potential		
	Mean (TJ)	Confidence interval (95% probability)	
Agricultural residues	25642	-67%	76%
Animal waste	23202	-37%	41%
Forestry	23040	-73%	92%
Urban waste	6722	-46%	60%
Total	78607	-36%	39%

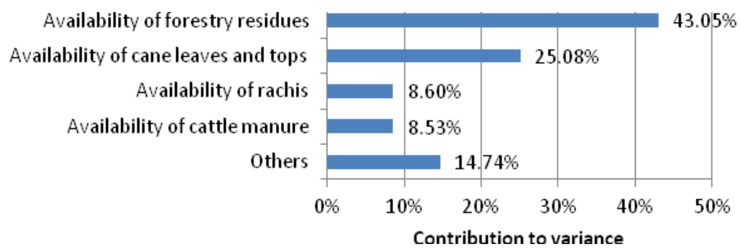

Table 8 Availability of resources for energy production in the baseline scenario

	Resource	Current use	Availability	Preliminary availability factor	Type of distribution	References
Agricultural residues	Cotton	Animal feed	×			
	Palm Oil	Heat	✓ Rachis	0-1	Uniform	[75], [76], [77]
	Cane (large)	CHP	✓ Leaves, tops	0-0.5	EUD	[74], [75], [78]
	Cane (small)	Heat, animal feed	×			
	Coffee	Fertilizer	×			
	Corn	Animal feed	×			
	Rice	Waste, fertilizer	✓ Husk	0-0.44	EUD	[29]
	Banana	Fertilizer, animal feed	×			
	Plantain	Fertilizer, animal feed	×			
Animal waste	Cattle	Waste	✓	0.12-0.24	EUD	[5]
	Pork	Waste	✓	0.07-0.14	EUD	[5]
	Poultry	Fertilizer	×			
	Equine	Waste	×			
Forestry	Wood fuel	Heat	×			
	Forestry residues	Soil replenishment	✓	0-0.5	EUD	[29], [31], [32]
	Ind. residual wood	Marketable by-product	×			
Urban waste	Landfill gas	Waste	✓	0.5-0.9	EUD	[50]
	W. market residues	Animal feed	×			
	Pruning	Animal feed	×			

4.4.2 Improved calculation of the technical biomass energy potential

The technical potential is recalculated using the improved estimation of key parameters and compared to the preliminary estimation (see Figure 6). Results for the recalculated potential (58904 TJ) are 25% lower than results for the preliminary potential (78607 TJ). In addition, the uncertainty associated to the recalculated case is significantly lower (-22%, +24%) than that of the preliminary case (-36%, +39%). This is a consequence of a better estimation of the availability factors, which after a thorough literature search and improved models tend to be lower and with a smaller associated uncertainty than in the preliminary estimation. While an important reduction in uncertainty is particularly obtained for the categories of animal waste (from 37-40% to 19%) and forestry residues (from 73-92% to 29-37%), this reduction is marginal for agricultural residues (from 67-76% to 60-69%). One of the reasons for this marginal reduction is the large uncertainty in estimating the volume of residues currently used for non-energy purposes, e.g. the rachis of the palm oil tree. Nevertheless, the results confirm the effectiveness of the sensitivity analysis followed by an improved estimation of key parameters.

Biomass categories	Technical potential (preliminary)		Technical potential (improved)	
	Mean (TJ)	**C.I. (95%)**	**Mean (TJ)**	**C.I. (95%)**
Agricultural residues	25642	-67%, 76%	16854	-60%, 69%
Animal waste	23202	-37%, 41%	17229	-19%, 19%
Forestry	23040	-73%, 92%	18185	-29%, 37%
Urban waste	6722	-46%, 60%	6716	-45%, 60%
Total	78607	-36%, 39%	58984	-22%, 24%

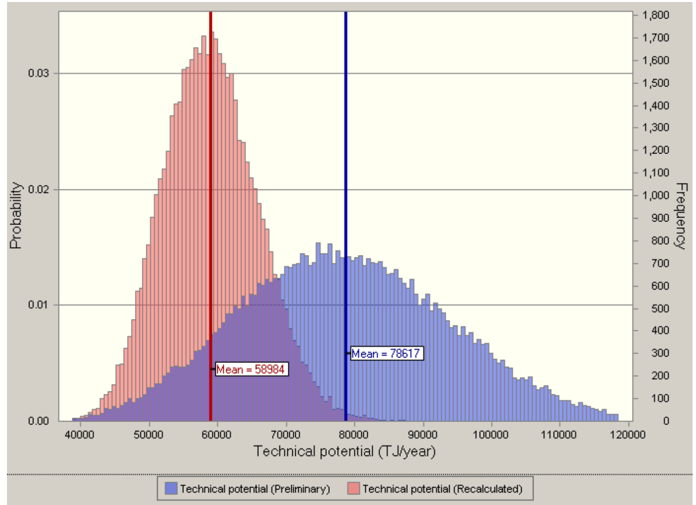

Figure 6 Preliminary vs. improved technical potential

4.5 Calculation of the current biomass energy utilization

The current biomass energy utilization is estimated as the theoretical potential associated to certain biomass categories used for energy production. These categories include cane bagasse at large- and small-scale, stone and fiber of the palm oil tree and wood fuel (see Figure 8). It amounts to 211074 TJ with a confidence interval of -11.4%, +12.5% at 95% probability.

4.6 Re-evaluation of other studies

Results of other studies were re-evaluated using the methodology explained before and the published assumptions. Information from the dataset presented in section 4.3 has been employed in cases where the methodology or assumptions used by the different reports are either not published or inconsistent. Examples include the calculation methodology used in the AENE and UPME report as well as some assumptions in the reports by Escalante et al., Arias et al. and Kline et al. Results are reported in Figure 7 and Figure 8. According to the hypotheses made, this study predicts a mean theoretical energy potential of 0.744 EJ with a confidence interval of -7.3%, +7.8% at 95% probability. This value is higher than the re-evaluated results of other studies. The main reasons for a higher estimation include: 1) this study includes agricultural residues, animal waste, forestry and urban waste, while most former studies evaluated only three of these categories, 2) this study includes both wood fuel and forestry residues, while previous reports considered one of two and 3) it assesses the potential for a more recent year (2010) compared to some of the previous studies. Most relevant categories for the theoretical biomass energy potential include agricultural residues (53%), forestry and wood industry (22%) and animal waste (24%). Contribution from and urban waste is marginal and accounts for 1% of the theoretical potential.

The predicted maximum technical potential is 58984 TJ with a confidence interval of -22%, +24% at 95% probability. The most relevant biomass categories are agricultural residues (29%), forestry (31%) and animal waste (29%), while urban waste contributed to the remaining 11%. The estimated technical potential is lower than three of the four existing studies due to various reasons. Firstly, this study does not include the potential of biofuels (secondary energy resources/carriers). Secondly, biomass resources that currently compete with other uses are not accounted. Thirdly, it attempts at describing more accurately the availability factors for the different biomass resources, which resulted in lower values compared to Arias et al. and AENE. Re-evaluated results from other studies do not always match published results. The main reason for this discrepancy can be attributed to the use of different assumptions and methodologies that are not originally available in previous reports. A notable mismatch is found for predictions of AENE and Arias et al. (for the latter, particularly in the category of animal waste). In summary, compared to prior art, the theoretical biomass energy potential estimated in this paper might be considered all-embracing, while the estimated technical biomass energy potential might be considered fairly conservative.

The current biomass energy utilization estimated in this study (211 PJ) is higher than three of the existing studies but is very similar to the official value (209 PJ) reported by the Mining and Energy Planning Unit (UPME). The estimated current biomass energy utilization accounts for 4.2% of the current primary energy supply (4.93 EJ). This contribution can increase to 5.47% (270 PJ) by exploiting the technical potential. Moreover, the amount of biomass not available for energy production at current conditions and constraints amounts to 479 PJ, which is 64% of the technical biomass energy potential in the country (excluding above-ground biomass in forests).

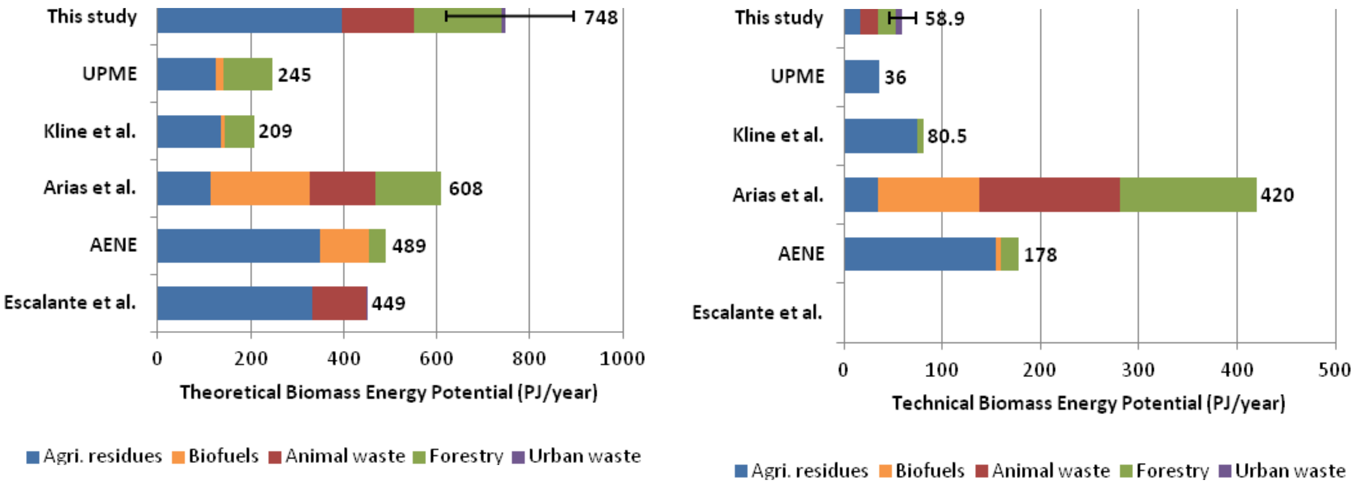

Figure 7 Comparison of the theoretical and technical biomass energy potential (C.I. of 95% probability)

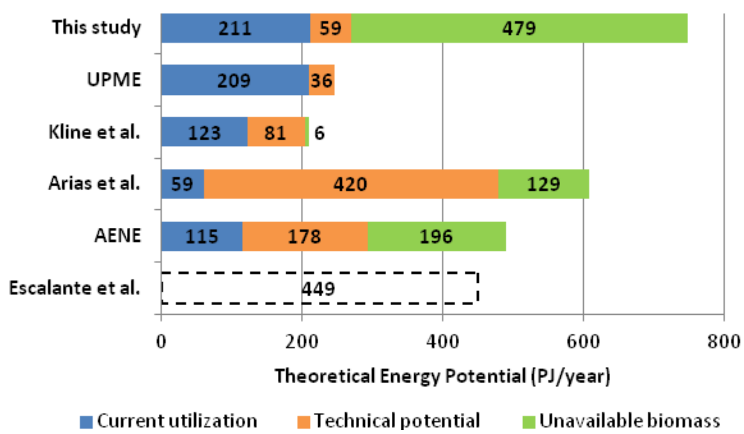

Figure 8 Comparison of the current biomass energy utilization and the technical potential

5. CONCLUSIONS

This paper presents a methodology to estimate the biomass energy potential and its associated uncertainty at a country level when quality and availability of data are limited. The proposed methodology is a bottom-up resource-focused approach with statistical analysis that uses a Monte Carlo algorithm to stochastically estimate the theoretical and the technical biomass energy potential. This paper also includes an approach to quantify the uncertainty of energy potential estimation, by combining a probabilistic propagation of uncertainty, a sensitivity analysis and a set of disaggregated sub-models to estimate reliability of predictions and reduce the associated uncertainty.

The current biomass energy potential in Colombia is assessed following the proposed methodology and results are compared to existing assessment studies. Obtained results show that it is possible to envision a theoretical energy potential of 0.744 EJ with a confidence interval of -7.3%, +7.8% at 95% probability, which might be considered all-embracing. This potential excludes the above-ground biomass in forests. If above-ground biomass in forests is included, then the theoretical potential can grow up to 219.88 EJ. However, a high uncertainty in this estimation is evidenced by a confidence interval of -45.5%, +46.0% at 95% probability. The effectiveness of the proposed method was proved by significantly reducing the uncertainty in predicting the theoretical and the technical biomass energy potential.

Results from previous studies are re-evaluated and compared following the proposed methodology. Despite large differences in results, there is agreement across studies that most relevant biomass categories include agricultural residues, residues from forestry and wood industry and animal waste. As a conclusion, this paper provides a complete and detailed framework to estimate the biomass energy potential at a country level and is applied to a case study of Colombia. This methodology is characterized by its transparency, reproducibility, low cost and possible adaptability to other countries. Various aspects require further attention in future work, e.g. scenario analysis to understand the influence of technology deployment on the technical potential, as well as dedicated measurement campaigns to assess the availability of biomass resources (e.g. rachis of palm oil tree, cane leaves at tops, forestry residues, etc.) at a local scale.

ACKNOWLEDGEMENT

Authors would like to express their gratitude to Trevor Kirsten, Renato Umeton, Helmer Acevedo, Anselm Eisentraut, Regis Lima Verde Leal, Jesus Gonzalez and María Fernanda Gonzalez for their support and advice to conduct this investigation.

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