Techno-Economic Estimation of the Power Generation Potential from Biomass Residues in Southeast Asia

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Abstract

Power generation from biomass residues is an attractive option for supplying the rapidly growing power demand of the Association of South East Asian Nations (ASEAN) in a sustainable and a cost-effective manner. In this paper, we assess the total quantity and location of biomass residues from agriculture, livestock and forestry activities in ASEAN, evaluate their technical power generation potential and estimate the cost of electricity production from these residues. A cost optimization model is developed to analyze cost-effective options to produce electricity from biomass residues using various conversion technologies. We estimate the total available thermal energy from biomass residues in ASEAN to be approximately 1076 TWh. About 86 % of the total energy potential is provided by agricultural residues, with rice, sugarcane and palm oil residues being the major contributors. We find the highest energy potentials to be located in Indonesia (407 TWh), Thailand (194 TWh) and Vietnam (153 TWh). The maximum technical potential for electricity generation from biomass residues in ASEAN amounts to 360 TWh. Power generation costs are within a wide range from less than 40 USD/MWh to more than 200 USD/MWh.

Keywords:

Renewables; Biomass-residues; Power generation; Cost optimization; Waste-to-energy; GIS; Binary-linear programming; Cost supply curves;

1 Introduction

The Association of Southeast Asian Nations (ASEAN) is experiencing a rapid economic growth, with its total GDP increasing by 93 % between 2000 and 2013 [1]. Coupled to this sturdy economic development is an even stronger increase of electricity generation, which grew by 112 % (from 374 TWh to 796 TWh) between 2000 and 2013 [2]. The International Energy Agency (IEA) predicts this rapid increase of power generation in ASEAN to continue, projecting an average annual growth rate of 4.2 % , reaching a value of 1900 TWh by 2035 [3]. Though natural gas still has the highest share in the power generation mix of ASEAN, coal-fired generation contributed most to supply the increasing power demand within the last decade [3]. Covering the increasing power demand mainly by coal would lead to a massive increase in the release of greenhouse gas (GHG) emissions. Hence, the question on how the future increase of GHG emissions in ASEAN can be mitigated cost-effectively, for example by using higher shares of renewable energy sources for power generation, needs to be addressed.

Power generation from biomass offers an advantage over other renewables such as solar and wind in terms of non-intermittency and ease of control. Considering only residues from agriculture, livestock and forestry activities for power generation avoids conflicts of using agro-resources for energy purposes over food production. Since agricultural production plays a major role in most ASEAN economies, large amounts of biomass residues are available. Besides that, anaerobic degradation of organic material in landfill could cause emission of methane leading to net positive GHG emissions from landfills [4]. Using biomass residues for power generation contributes to mitigate the increase of GHG emissions in ASEAN and also to counter the problems associated with waste pileup.

In this study we focus on electricity production from available biomass residues in ASEAN. The major objectives of this work are to evaluate the amount and the locations of biomass residues available for power generation in ASEAN and to estimate the technical potential and cost of electricity production from these residues. Of the various energy products convertible from biomass residues, we restrict this study exclusively to power generation. In our study, we consider a variety of biomass residues of agriculture (e.g. straw, husk, etc.), livestock (manure) and forestry (logging residues). The electricity production technologies considered in this study include co-firing in existing coal power plants, direct combustion, gasification and anaerobic digestion.

We develop an optimization model that minimizes the total cost of power generation for a given quantity of electricity generated from biomass residues. As a result, we derive cost supply curves of power generation from biomass residues for each ASEAN country.

In Geographic Information System (GIS), geo-spatial data is stored in layers that represent georeferenced measures of a geographical variable [5]. GIS-based approaches have been used to analyze energy potentials from various renewable energy sources [6]. In this paper, we use QGIS software (version 2.8.2 [7]) to edit and combine geo-spatial datasets in order to derive estimations on the spatial distribution of available biomass residues and to determine optimization model input parameters.

There are numerous studies on the power generation potential of biomass residues in ASEAN available in the literature. Most of the existing work either focuses on selected countries [8–11], generation technologies [12] and/or biomass types [13,14]. Moreover, current studies are based on different assumptions (e.g., on residue availability or conversion efficiencies) and/or methods (e.g., in estimating the locations of available biomass residues). Hence, it is difficult to compare the results of existing biomass potential studies among the ASEAN countries. Furthermore, most of the existing studies analyze the power generation potential from biomass residues on a national level and don’t approximate the location of available residues (e.g., by using GIS-approaches) [8,9,11,15]. Besides that, existing work often focuses either on estimating the potential energy available from biomass residues (without considering conversion to electricity) or on analyzing the logistic costs and/or the optimal location and sizing of bio-energy plants [16,17] , but doesn’t combine both the aspects.

To the best of our knowledge, this paper is the first study that analyzes GIS-based estimations of power generation potentials from agricultural, forestry and livestock residues in such a detail for the entire ASEAN, and combines these results with a power supply cost minimization model. We formulate a uniform methodology to compare the power generation potentials from residual biomass among the ASEAN countries. Besides that, we include most updated production data on a wide range of biomass products from agriculture, livestock and forestry, and estimate the location of their residues in high spatial resolution. Furthermore, by estimating the costs of fuel, power plants and transportation, we are able to evaluate the economics of using biomass residues for power generation on an ASEAN-wide scale.

The following section 2 presents the developed optimization model. In section 3, the methodology to estimate the available energy from biomass residues in ASEAN is described. The results of this study are shown in section 4, followed by a conclusion of our work in section 5.

2 Optimization Model for Biomass Usage for Power Generation

In this section, we give a short description of the analyzed problem and provide a mixed binary-linear programming cost minimization model to study cost effective power generation from biomass residues.

We present the general model framework which is applied to each country individually. The optimization model is formulated in Python [18] (version 2.7.10) and solved using Gurobi (version 6.05) on a Dell Precision T7910 with 128 GB of RAM.

2.1 Problem Description

The aim of this study is to estimate the potential quantity and the approximate cost of electricity generated from biomass residues available in ASEAN. Specific power generation costs depend on the cost for fuel, transport and the power generation technology. As the biomass residues can be converted to electricity using different generation technologies (with different conversion efficiencies and costs), the potential quantity of electricity produced depends on the applied conversion technology. Hence, the objective is to develop a model to determine the total cost and the conversion technologies (type, location and capacity) necessary to provide a given quantity of electricity most cost-effectively, using the biomass residues available. As a major model assumption we consider the available residues to be located at centroids of model areas, which is described in greater detail in section 2.3.1. The estimated fuel cost includes collection cost within the model areas. Costs of transport between model points is modelled separately. Besides that, despite the multiple possible pathways of using biomass residues for energy conversion (e.g., different options of densification or transport), we assume specific process chains (defined in section 2.3.6 based on similar fuel characteristics) to use the considered residues for power generation.

2.2 Optimization Model Formulation

Different biomass residues b are available at model points l, where they can be used for electricity production by installing generation capacity c_{lbt} of conversion technology t, generating an annual electric output of g_{lbt}. Instead of usage for power generation at model points l, the biomass residues can be transported to other model points l'. Set A includes all possible transportation routes between the model points. We define separate sets EX_l and IM_l of possible export destinations, respectively import origins of model points l.

The total cost of power generation and transport of the biomass residues given in the objective function (1) is minimized. The power generation costs include investment costs, fixed and variable O&M costs as well as costs for fuel (collection and processing of the biomass residues) and depend linearly on the generation capacity and the annual electric output. The cost for biomass transport increases linearly with distance and transported energy.

Equation (2) defines the correlation between annual (electric) power output and (thermal) energy input from biomass residues, using the technology-specific conversion efficiency η_t. Feasibility factors m_{bt} and p_{lt} are defined which are set to 1 if the respective combination of generation technology and residue/location is feasible (assumptions on feasible options are presented in section 2.3.3), and to 0 if otherwise.

The annual electric output of the installed generation capacities is limited by the assumed annual full load hours of operation of the respective conversion technology, described in (3).

To avoid unrealistically small generation capacities and to consider upper limits of installable generation capacities (e.g., for co-firing), we introduce lower and upper boundaries for the capacity of the generation technologies installed at each model point, given by (4) and (5).

Restriction (6) describes the conservation of energy at each model point.

The minimum electricity that has to be generated in each scenario is defined by restriction (7), and is based on a share of the maximum country-wide producible electricity from biomass residues $elecmax$ (explained more in detail in section 2.3.4).

Minimize Cost:

$$\sum_{l\in L}\sum_{b\in B}\sum_{t\in T}[inv_t + Of_t]\cdot c_{lbt} + \sum_{l\in L}\sum_{b\in B}\sum_{t\in T}(Ov_t\cdot g_{lbt} + f_b\cdot i_{lbt}) + \sum_{ll'\in A}\sum_{b\in B} r_b\cdot d_{ll'}\cdot e_{ll'b} \tag{1}$$

Subject to:

$$g_{lbt} = i_{lbt}\cdot \eta_t\cdot p_{lt}\cdot m_{bt} \qquad \forall\, l\in L,, \forall\, b\in B, \forall\, t\in T \tag{2}$$

$$g_{lbt} \leq c_{lbt}\cdot FLH_t \qquad \forall\, l\in L,, \forall\, b\in B, \forall\, t\in T \tag{3}$$

$$\sum_{b\in B} c_{lbt} \leq x_{lt}\cdot cmax_t \qquad \forall\, l\in L, \forall\, t\in T \tag{4}$$

$$\sum_{b\in B} c_{lbt} \geq x_{lt}\cdot cmin_t \qquad \forall\, l\in L, \forall\, t\in T \tag{5}$$

$$a_{lb} - \sum_{l'\,\in\, EX_l} e_{ll'b} + \sum_{l''\,\in\, IM_l} e_{l''lb} \geq \sum_{t\in T} i_{lbt} \qquad \forall\, l\in L, \forall\, b\in B \tag{6}$$

$$\sum_{l\in L}\sum_{b\in B}\sum_{t\in T} g_{lbt} \geq h\cdot elecmax \tag{7}$$

$$m_{bt} = \begin{cases} 1, if\ biomass\ residue\ b\ can\ be\ converted\ into\ electricity\ using\ generation\ technology\ t \\ 0, otherwise \end{cases}$$

$$p_{lt} = \begin{cases} 1, if\ generation\ technology\ t\ can\ be\ installed\ in\ model\ point\ l \\ 0, otherwise \end{cases} \tag{8}$$

$$c_{lbt} \geq 0 \qquad \forall\, l\in L,, \forall\, b\in B, \forall\, t\in T$$

$$g_{lbt} \geq 0 \qquad \forall\, l\in L,, \forall\, b\in B, \forall\, t\in T \tag{9}$$

$e_{ll'b} \geq 0$ $\forall\, ll' \in A, \forall\, b \in B$

$i_{lbt} \geq 0$ $\forall\, l \in L,, \forall\, b \in B, \forall\, t \in T$

x_{lt} binary $\forall\, l \in L, \forall\, t \in T$

2.3 Estimations and Assumptions of Model Input

2.3.1 Definition of Model Points

The model points l consist of centroids of administrative model areas taken from [19], and the locations of coal power plants in ASEAN with 50 MW minimum generation capacity. In case an administrative model area comprises several islands or both mainland and islands, separate model points are defined for each island to avoid sea transport of biomass residues. The considered model areas and locations of coal power plants are illustrated in Figure 1. The number and the administrative level of the considered areas of each country are given in Table A2 in the annex. The estimation of the available energy from biomass residues at each model point is given in section 3.

2.3.2 Technical and Economic Parameters of Generation Technologies

The technical and economic parameters of the generation technologies considered in this study are obtained from the literature [9,20] and listed in Table 1. The cost parameters of the generation technologies are average values taken from the cited references. Only for co-firing an upper limit of generation capacity is applied and set to 10 % of the generation capacity of the respective coal power plant.

2.3.3 Definition of Technically Feasible Generation Options

Table 2 gives an overview of all the biomass products and residues considered. To define the values of the binary indices m_{bt} and p_{lt} we categorize biomass residues, generation technologies and model points into different classes, illustrated by Figure 2. The generation technologies are classified into co-firing, thermochemical (direct combustion and gasification) and bio-chemical (anaerobic digestion) conversion. Biomass residues are distinguished between residues used in thermo-chemical conversion processes (all forestry and agricultural residues except POME) and residues which can be used in bio-chemical conversion technologies (POME and all livestock residues). We define that all power plants can be installed only at the aforementioned centroids of administrative areas which are located within a corridor of 25 km around currently existing or planned transmission lines. Data on currently existing and planned transmission network in Southeast Asia are taken from national power supply utilities of each country, geo-referenced using QGIS, and are illustrated in Figure 1. The model points are classified as locations of coal power plants, centroids of model regions in which power plant construction is feasible and the points outside the corridor of transmission lines. The feasible combination for the definition of m_{bt} and p_{lt} matrices are marked by dashed line in Figure 2.

2.3.4 Estimation of Maximum Producible Electricity by Country

The maximum producible amounts of electricity by country $elecmax$ are derived by applying the optimization model presented in the beginning of this section with slight modifications. Restriction (8) is skipped, and the objective function (1) is substituted by (10), in which the electric output of an entire country is maximized.

Maximize Electric Output:

$$\sum_{l\in L}\sum_{b\in B}\sum_{t\in T} g_{lbt} \tag{10}$$

2.3.5 Estimation of Transport Parameters

To reduce the number of tuple entries of A, we assume that biomass residues can directly be transported from each model point only to its six closest neighboring model points. As from these six closest neighbors, biomass residues can be transported to their respective six closest neighbors, the transport of residues to distant model points is possible.

The distances between the model points are determined as shortest road distances, using data on road network from [31], and the Dijkstra-algorithm to find the shortest possible route between the model points. In case no possible transport route between two model points can be found, the respective route is not considered in A.

The specific transport costs of residues per distance and energy are based on the cost model for biomass transport presented in [17]. All cost data given in [17] are adjusted to the year 2015 using adjustment factors from [32], and the average travel speed is set to 35 km/h. We assume the time for loading/unloading to amount to 25 % of the driver’s working time. Table 3 summarizes the assumptions to calculate the specific costs for transportation.

We consider country-specific costs for diesel and hourly pay rates for drivers. Costs for diesel are taken from [33]. To estimate the hourly pay rate for drivers, most recent data on average monthly wages for each country are taken from [34] and adjusted to the year 2015. A linear regression between GDP/Capita in current USD (taken from [33]) and monthly average wage is used to estimate the monthly average wage for countries where this data is not directly available.

Depending on the transport density of the biomass residues, the maximum amount of biomass that can be transported within a single trip is limited either by maximum volume or the maximum load of the considered trailers. Table 4 shows the transport densities, which are in accordance to the respective process chains introduced in in section 3.2.6. For coconut husk and shell, coffee husk and groundnut shell, no adequate density values after briquetting is found in the literature. Hence, we assume a value of 423 kg/m³ in these cases, to define maximum load as the limiting factor for transportation.

2.3.6 Fuel Cost of Biomass Residues

As fuel costs we consider the cost for raw materials of the biomass residues along with the cost of preparing, handling and storing processes (except transport cost). Based on similar characteristics of the residues, e.g. the site where the residues are available (field based or process based) or their physical properties (liquid or solid), we group the biomass residues and define process chains of fuel preparation for each group of residues. The considered biomass residue groups, the relevant process chains and the derived fuel costs are summarized in Table 5.

Agricultural residues

For agricultural biomass, we distinguish between process and field based residues. For field based residues, we assume that the residues are collected and baled first, and later grinded at the power plant. For process based residues, no collection is required, and we assume that the residues are briquetted before usage for power generation or transportation. For all the residues, we consider costs for handling and storing. Compared to all the other agricultural residues, POME shows quite different characteristics (liquid, low LHV, limited options for alternative usage). Hence, we consider the fuel cost of POME separately, and assume no fuel costs, as it is on site available and hardly requires any additional fuel preparation.

Forestry residues

We assume that the logging residues from forestry are piled, bundled and grinded before using them for power generation.

Livestock residues

For residues from livestock, we assume the available residues are used directly for power generation without major pre-processing. Hence, we only consider costs for manure, handling, receiving and storing as fuel costs of livestock residues. As an estimation of the costs for manure, handling, receiving and storing, we use the distant fixed transportation cost (DFC) for slurry manure given in [41]. Here, we apply the DFC of slurry manure for residues from cattle, buffalo and pig, and the DFC of solid manure for poultry, sheep and goat. The costs for manure from cattle, buffalo and pig are based on the dry share of the respective manure, whereas the cost for manure from poultry, sheep and goat are based on their total mass, assuming 5 USD per ton of manure.

3 Estimating the Available Energy from Biomass Residues

Geo-spatial raster grids of biomass production are developed and used along with estimations of available energy per biomass product to derive the distribution of energy available from each biomass residues in a high spatial resolution. Based on that, the available energy from biomass residues at each model point is derived.

3.1 Deriving Geo-Spatial Grids of Biomass Production

Most recent data on the production of different agricultural and forestry products and on the livestock of various animals are collected on a detailed administrative level. Country-wide data from [43] are used in case regional data isn't available

Table A.1 in the annex lists the number of regions within each country, for which agricultural production or livestock data are collected.

Since the collected production data are available for different years they are adjusted to the annual production in reference year 2013 taken from [43], using country-wide constant adjustment factors.

The biomass production and livestock data are rasterized in QGIS and weighed (using the 'raster calculator' function) by high resolution geo-spatial grids which are based on land use data (for agricultural and forestry biomass) or existing raster grid models (for livestock) and explained more in detail in the following sub-sections.

3.1.1 Agricultural Biomass

Data of agricultural biomass production are collected for 830 administrative areas in ASEAN from [43–51]. The adjusted production data are mapped to a raster grid with a cell size of 15 arc seconds (approx. length of 450 m at the equator), using land-use data from [52]. The collected production data of each administrative area are distributed to its comprising cells of land use types "Croplands" and "Cropland/Natural Vegetation Mosaic" (land use type 12 and 14 respectively in [52]), assuming the cells of land use type "Croplands" to have twice as much production compared to the cells indicated by "Cropland/Natural Vegetation Mosaic".

3.1.2 Forestry Biomass

For forestry biomass, no consistent production data in high spatial resolution is found. Hence, country-wide annual production data for the reference year 2013 are taken from [43]. The annual production of wood is converted from volume to mass using a density of 0.75 tons/m³ [53] for coniferous wood and of 0.85 tons/m³ [53] for non-coniferous wood. The forestry production data of each country are evenly distributed to all comprised raster cells from [52] (cell size of 15 arc seconds) which indicate any type of forest as major land use type (land use types 1,2,3,4 and 5 in [52]). Raster cells which are located in protected areas (taken from [54]) or within intact forest areas which still remain mostly untouched by humans (taken from [55]) are not considered in the distribution of forestry biomass.

3.1.3 Livestock

Livestock data is collected for 754 administrative areas in ASEAN from [43–45,56–59]. The adjusted livestock data are distributed within each area according to the distribution given in the livestock grid model published in [60], which is in a grid resolution of 30 arc seconds.

3.2 Estimating the Available Energy based on Biomass Production and Livestock

As the biomass production and livestock data described above are available in different physical units, the method to estimate the available residual energy differs for agricultural and forestry biomass compared to livestock

3.2.1 Agricultural and forestry Raster Grids

The mass of the biomass residues produced is calculated by multiplying the production data per cell of each biomass product with its respective residue-production-ratio (RPR). The RPR indicate the mass of residue produced per unit mass of biomass product and are listed in Table 2. RPR values vary widely between the different residues and crops owing to its physical nature. A wide range of RPR values are available in literature. The most appropriate values were chosen after careful considerations. As a share of the considered biomass residues could already be utilized for other purposes (e.g., as natural fertilizer, animal feed, etc.), availability factors af (shown in Table 2 are applied to estimate the actual amount of residues available for power generation. To convert the available quantity of residues into available energy per grid cell, lower heating values (LHV) of the biomass residues are used, which are presented in Table 2. The applied values of RPR_b and LHV_b (for each biomass residue b) are based on the same moisture content. The available energy of each residue in each grid cell is calculated according to Equation (11).

$$a_{cb} = BP_{xc} \cdot RPR_b \cdot LHV_b \cdot af_b \tag{11}$$

3.2.2 Livestock Raster Grid

For livestock, the RPR values shown in Table 2 indicate the annual production of volatile solid (VS) mass of manure per animal. The LHV of livestock is the product of the respective possible methane production per ton of VS of each animal taken from [30] and the energy density of methane. The available energy from livestock residues is calculated in analogy to agricultural and forestry biomass, described by Equation (12).

$$a_{cb} = NL_{xc} \cdot RPR_b \cdot LHV_b \cdot af_b \tag{12}$$

3.2.3 Available Energy at Model Points

The available energy a_{lb} of the biomass residues at each model point is determined using the residue-specific raster grids developed in section 3.1 and is calculated by the summation of all cell values of the raster grids which lie within the respective administrative model area, which is described by Equation (13). This summation is provided by the QGIS function ‘zonal statistics’.

The model areas used to define the model points are in a higher resolution compared to the administrative areas for which reported biomass production or livestock data are collected. Hence, by using the geo-spatial raster grids developed in section 3, the collected data on biomass production and livestock is allocated from coarser to finer administrative areas.

$$a_{lb} = \sum_{c \in Z_l} a_{cb} \tag{13}$$

4 Results

4.1 Available Biomass Residues

The resulting energy from all available biomass residues is summarized by country in Table 6. Indonesia offers most available energy from biomass residues in ASEAN (407 TWh), followed by Thailand (194 TWh), Vietnam (153 TWh) and the Philippines (118 TWh). In whole ASEAN, agricultural residues account by far for the highest amount (928 TWh) of the available energy, followed by residues from forestry (109 TWh) and livestock (39 TWh).

Residues from rice (rice straw 416 TWh, rice husk 97 TWh) have the highest amounts of available energy from agricultural biomass, followed by sugarcane (leave and top 111 TWh, bagasse 18 TWh), oil palm (EFB 51 TWh, POME 17 TWh, frond 14 TWh, fiber 13 TWh, shell 3 TWh), maize (stalk 52 TWh, cob 31 TWh) and coconut (husk 33 TWh, frond 27 TWh, shell 10 TWh).

A more detailed overview of available energy resources by country and residue is given by Table A.3 in the annex.

In Figure 3, a raster grid of the total available energy from all biomass residues (derived by the summation of the raster grids of each individual residue) shows the distribution of the estimated biomass potential within ASEAN. Highest energy densities from available biomass residues can be found close to highly populated areas (on Java, around Hanoi, Ho Chi Minh, Bangkok, Yangon, Manila and the east coast of Peninsular Malaysia) as well as along major rivers (e.g., along the Mekong, Irrawaddy, Red River, Chao Phraya).

4.2 Optimization Results

The maximum producible electricity from biomass residues $elecmax$ for each country is given in Table 6 and compared to the power demand of the respective countries in 2013 which is taken from [1,2]. With 132 TWh, Indonesia offers the highest technical potential for electricity production from biomass residues, followed by Thailand (66 TWh), Vietnam (52 TWh) and the Philippines (39 TWh). On the contrary, the potential for power generation from residual biomass in Singapore and Brunei is close to zero.

The share of current power consumption that technically could be provided by electricity generation from biomass residues varies strongly among the ASEAN countries. On the one hand, in Brunei, Indonesia, Malaysia, the Philippines, Singapore, Thailand and Vietnam, only a part of the power consumption could be covered by electricity from biomass residues (from 0 % in Singapore to approx. 70 % in Indonesia). On the other hand, the power generation potential from residual biomass in Laos, Cambodia and Myanmar exceeds their current power consumption by 38 %, 181 % and 268 % respectively.

If electricity quantities smaller than $elecmax$ are generated, technologies and fuels with high specific generation costs (and efficiencies) would partially be replaced by technologies with lower specific generation costs but lower conversion efficiencies. Hence, the technologies and fuels used for power generation that lead to minimum total generation cost depend on the amount of electricity which is produced. Therefore, we apply the optimization model presented in section 2.2 with the objective function (1) for each country with different amounts of generated electricity, increasing the share h in (7) in steps of 10 percentage points from 10 % up to 100 % (h values of 0.1 to 1*)*.

Figure 4 shows the resulting cost-supply curves of Indonesia for the cases in which 60, 80 and 100 percent of the maximum producible electricity are generated. The cost-supply curves in Figure 4 include fuel costs, power plant costs, and transport costs. The costs for fuel, power plant and transport of each residue at each power plant are divided by the electricity generated from the respective fuel in order to receive the cost-supply curve in Figure 4, where power generation costs are sorted in ascending order.

As described in section 3.2, residues from forestry and agriculture (except POME) could be used either for co-firing, direct combustion or gasification. With the assumptions given in Table 1, co-firing offers high efficiencies and lowest power plant costs compared to other generation technologies. This leads to comparably low power generation costs by co-firing, what is shown by Figure 4. Hence, once the maximum power generation from co-firing is reached and total electricity to be generated is increased, agricultural (except POME) and forestry residues are mainly converted into electricity by direct combustion, which offers lower LCOE (but also a lower conversion efficiency) compared to gasification. This is shown in the 60 percent case (h=0.6) in Figure 4. As illustrated in the 80 (h=0.8) and 100 percent (h=1.0) case in Figure 4, direct combustion is more and more replaced by gasification with higher quantities of generated electricity, as it offers higher conversion efficiencies (but also higher specific generation costs) compared to direct combustion.

As fuel costs (in [USD/MWh]) vary significantly among POME and the livestock residues (shown by Table 4), power generation costs using anaerobic digestion are within a wide range, as shown in Figure 4.

As illustrated by Figure 4, an increase in minimum quantity of generated electricity does not result in a pure extension of the cost supply curves. It rather affects the generation technologies used to convert the available biomass residues.

Figure 5 shows the average power generation costs for different levels of power generation to compare the techno-economic potentials of using biomass for power generation in different countries. We calculate the average power generation costs by dividing the total cost of power generation (described in the objective function (1)) by the amount of electricity which produced in the respective case. The average power generation costs from biomass residues increase with higher quantities of generated electricity.

In Indonesia, Malaysia, Vietnam, Thailand and the Philippines using co-firing for power generation is possible, as significant coal-fired generation capacity is installed. Hence, with low shares of the maximal electricity potential being generated, average power generation costs in these countries are quite low (around 35 to 60 USD per MWh). As power generation from co-firing is limited by the capacity of coal power plants, additional power generation is mainly provided by direct combustion, which is replaced by gasification with high quantities of electricity, like described previously. Besides that, more expensive residues from livestock are used for power generation. Both effects increase the average power generation costs.

As in Cambodia, Laos and Myanmar, no significant coal-fired generation capacity is installed, there is no opportunity of using co-firing for power generation. Thus, direct combustion and gasification are used for power generation using agricultural and forestry residues. This is reflected in higher specific cost for power generation at lower h values in comparison to the other countries with co-firing option available. Power generation potentials in Singapore and Brunei are quite limited and mainly consist of anaerobic digestion using livestock manure, which is characterized by comparably high LCOE.

Figure 6 shows the sensitivity of the power generation cost to the various input costs for different quantities of power generation in Indonesia. The fuel cost, power plant cost and transport cost are changed ceteris paribus by ± 30 %.

Power generation cost is very sensitive to fuel and power plant costs. They vary from ± 20 % to ±11 % (for ± 30% change in fuel cost) and from ± 7% to ± 19 % (for ± 30% change in power plant cost) for different h values. At lower h values electricity is mainly generated by co-firing which has lowest power plant cost of all the generation technologies considered. With higher h values more expensive generation technologies are used for power generation which increases the share of power plant cost in the total cost of power generation. Hence, at low h values total power generation cost is more sensitive to fuel cost compared to power plant cost and vice versa with higher h values.

As seen from Figure 6, the power generation cost isn’t very sensitive to transportation cost. For lower quantities of power generation, the deviation is higher since the average transport distance of fuel to co-firing power plants is high (due to comparably high generation capacity and no available residues at coal power plant locations). However, in this work we only model the costs of biomass transport between model points explicitly. Transport costs which occur at residue collection are implicitly included in the fuel cost.

5 Conclusion

In this paper, the available energy from agricultural, livestock and forestry residues in ASEAN is estimated and located using data on current biomass production and high resolution geo-spatial raster data. The maximum amount of electricity that could be produced from these residues is evaluated. We developed an optimization model that minimizes total costs of power generation for a given quantity of electricity generated to analyze the economics of power generation from biomass residues in ASEAN.

Agricultural production accounts for most of the available thermal energy (a share of 86 %), with major contributions from residues from rice production, followed by residues from sugarcane and palm oil cultivation. It is found that energy from biomass residues is available especially at river basins and near densely populated areas.

Indonesia followed by Vietnam and Thailand offer most abundant biomass resources, as the agricultural sector plays an important role in their economies and they possess large land areas. In contrast, due to restricted land area and less economic significance of the agricultural sector, the potential for bioenergy in Brunei and Singapore is quite limited.

As cost for fuel and conversion technology lies within a wide range, power generation cost from biomass increase significantly with the amount of generated electricity.

Co-firing seems to be an economically attractive option to use biomass residues for power generation. However, we only take into account the additional costs to convert biomass residues by co-firing into electricity in this paper. We do not consider investment costs of the existing coal-fired generation capacity (which has to be in place in order to use co-firing) or cost savings by reduced coal consumption. On one hand, this approach may be justified to assess the conversion of available biomass residues with minimum additional costs. On the other hand, this reduces the comparability of co-firing with other generation technologies. Co-firing is especially interesting for ASEAN, where significant coal-fired generation capacity will probably be installed within the next decades. The new coal power plants could be designed and located to support co-firing of biomass.

Even though its applicability is still subject to current research, we consider thermo-chemical gasification as possible conversion technology for a wide range of agricultural and forestry residues, as we expect significant progress in future development here.

Moreover, as many residues can be used in multiple conversion technologies, the generation technologies that lead to minimum specific generation costs depend on the total amount of electricity that is generated within a country. With the assumptions in this paper on efficiency and generation costs which are based on recent estimations found in the literature, gasification offers higher efficiencies but also higher generation costs compared to direct combustion. Hence, thermo-chemical conversion is only used when total power generation from biomass within a country is close to its maximum country-wide technical potential. Higher future cost reductions for gasification compared to direct combustion could change this observation.

Due to its applicability in decentralized power supply systems and less capital intense investments, power generation from biomass could be an adequate option especially for less developed countries like Cambodia or Myanmar, where a reliable and country-wide transmission grid is not yet in place.

Using biomass for power generation offers the opportunity to reduce GHG emissions, but could also lead to increased emissions of dust and SO_2. Hence, more future work on the total emission reduction potential of biomass is required.

In our study, we analyze the power generation potential from biomass residues for entire ASEAN. This allows us to compare generation potentials and their generation costs between countries, but doesn't provide information on precise power plant locations. Furthermore, the usage of different residues within the same power plant could be more restrictive than assumed in this work. Even though this might not change the available energy, the maximum producible electricity and the power generation costs significantly (which are our primary objectives), it has a major influence on the location of possible power plants. Hence, to identify precise plant locations and feedstocks of individual power plants, more detailed studies have to be carried out in addition to this work, focusing on specific countries or sub-regions. Here, parameters such as RPR, availability factors, farmer premium, etc. which can vary over larger geographic extent could be made location specific to increase the accuracy of the results.

Furthermore, we focus this work on power generation from biomass residues to avoid both replacing food by fuel production and clearing of forest lands to cultivate energy plants. But increased usage of biomass residues increases their economic value and therefore the attractiveness to clear forest lands for biomass cultivation. Hence, adequate government policies are required in order to protect the eco-systems and biodiversity.

In future research, the results of this paper can be combined with techno-economic analyses of other renewable energy sources (wind, solar, geothermal etc.) in order to study possible generation capacity expansions for a cost-effective and sustainable power generation mix in ASEAN. We also plan to evaluate the environmental impacts of electricity generation from biomass residues in ASEAN through life cycle assessment techniques in the future work. The cost and emissions of biofuel production from biomass residues for ASEAN have to be analyzed as well. A sensitivity analysis of the developed model in this work will is planned to be presented in future work.

Acknowledgements

This work was financially supported by the Singapore National Research Foundation under its Campus for Research Excellence And Technological Enterprise (CREATE) programme.

The support by Newcastle University is gratefully acknowledged.

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Nomenclature:

Symbol	Unit	Explanation
X		Considered biomass products or livestock types, indexed by x.
C		Grid cells of the respective production grids, indexed by c
a_{cb}	MWh_{th}/a	Available annual energy from residue b at grid cell c.
BP_{xc}	ton/a	Annual production of biomass product x at grid cell c.
NL_{xc}	heads/year	Annual average number of livestock x at grid cell c.
RPR_b	ton/ton	Residue-production-ratio of residue b.
LHV_b	MWh_{th}/ton	Lower heating value of residue b.
af_b	-	Availability factor of residue b.
Sets		
Z_l		Set of cells which lie within the administrative area with model point l as centroid.
L		Set of model points (centroids of administrative areas and locations of coal power plants) within one country, indexed by l.
B		Set of biomass residues, indexed by b.
T		Set of generation technologies, indexed by t.
A		Tuple points where transport of residues is possible, indexed by ll'. The elements of this set are derived by pairing the indices of each model point $l \in L$ with each of its respective six closest neighboring model points $l' \in L$.
EX_l		Sets with the indices of the six closest neighboring model points of model point l: $EX_l = \{l' \mid ll' \in A\}$. On these arcs, residues can be exported from model point l.
IM_l		Sets with the indices of the model points where l is one of the six closest neighbors. $IM_l = \{l'' \mid l''l \in A\}$. On these arcs, residues can be imported to model point l.
Parameters		
inv_t	$USD/(MW_{el}\ a)$	Annualized specific investment costs of generation technology t
Of_t	$USD/(MW_{el}\ a)$	Annual fixed O&M costs of generation technology t
Ov_t	USD/MWh_{el}	Variable O&M costs per generated electricity of generation technology t
f_b	USD/MWh_{th}	Fuel cost of biomass residue b per thermal energy (based on LHV)
$d_{ll'}$	km	Distance between model point l to model point l’
r_b	$USD/(MWh_{th}\ km)$	Transport cost of biomass residue b per distance per thermal energy (based on LHV)
m_{bt}	-	Binary matrix entry indicating if biomass residues b can be converted to electricity using generation technology t
p_{lt}	-	Binary matrix entry indicating if generation technologies t can be installed at model point l
η_t	-	Efficiency of generation technology t, converting (thermal) energy input into electricity
FLH_t	h/a	Annual full load hours of operation of generation technology t
$cmax_t$	MW_{el}	Maximum installable power plant capacity of generation technology t
$cmin_t$	MW_{el}	Minimum required power plant capacity of generation technology t
$elecmax$	MWh	Maximum country-wide annually producible electricity
h	-	Minimal Share of $elecmax$ which is required to be generated annually

a_{lb}	MWh_{th}/a	Annually available energy (based on LHV) from biomass residue b at model point l
Variables		
c_{lbt}	MW_{el}	Electric generation capacity of generation technology t at power plant location l, using biomass residue b
g_{lbt}	MWh_{el} /a	Annual (electric) power generation of generation technology t at power plant location l, using biomass residue b
$e_{ll'b}$	MWh_{th}/a	Annually transported biomass residues b (in thermal energy, based on LHV) from model point l to model point l’
i_{lbt}	MWh_{th}/a	Annual(thermal) energy input (based on LHV) converted by generation technology t at location l, using biomass residue b
x_{lt}	-	Variable that indicates if generation technology t is installed at location t

Tables:

Table 1: Input parameters of considered power generation technologies [9,20]

Generation Technology t	inv_t [USD/(MW$_{el}$ a)]	Of_t [USD/(MW$_{el}$ a)]	Ov_t [USD/MWh$_{el}$]	η_t [-]	FLH_t [h/a]	$cmin_t$ [MW$_{el}$]
Direct Combustion	2,165,000	77,940	4.25	0.25	7500	4
Gasification	3,456,875	155,560	3.7	0.34	7500	5
Anaerobic Digestion	2,359,167	89,110	4.2	0.4	7500	0.3
Co-firing	500,000	15,000	0	0.35	8000	0.5

Table 2: Considered Biomass Residues and their values of RPR_b, LHV_b and af_b

Biomass Group	Biomass Product x	Biomass Residue b	RPR_b#	LHV_b [MWh/ton]*	af_b [-]	Source
Agriculture	Rice	Straw	1.00	3.89	0.50	[21,22]
	Rice	Husk	0.27	3.57	0.47	[15,22]
	Maize	Stalk	1.00	3.97	0.33	[23,24], Assumed
	Maize	Cob	0.25	4.62	0.67	[15]
	Sugarcane	Bagasse	0.25	1.79	0.21	[15]
	Sugarcane	Top & Leave	0.30	1.89	0.99	[15]
	Oil Palm	Shell	0.07	4.72	0.04	[25], [15]
	Oil Palm	Fiber	0.13	3.08	0.13	[25], [15]
	Oil Palm	Empty Fruit Bunches (EFB)	0.23	1.69	0.58	[25], [15]
	Oil Palm	Palm Oil Mill Effluent (POME)	0.67	0.17	0.65	[25],[26]
	Oil Palm	Frond	0.55	2.21	0.05	[25], [15], [26]
	Cassava	Stalk	0.09	4.72	0.41	[15]
	Coconut	Husk	0.36	4.09	0.60	[15]
	Coconut	Shell	0.16	4.58	0.38	[15]
	Coconut	Frond	0.23	4.04	0.81	[15]
	Coffee	Husk	2.10	3.44	0.33	[24] , Assumed
	Groundnut	Shell	0.32	3.12	1.00	[15]
	Groundnut	Straw	2.30	4.88	0.33	[27], [24], Assumed
Forestry	Industrial Roundwood coniferous	Logging Residues	0.67	4.31	0.40	[28,29]
	Industrial Roundwood non-coniferous	Logging Residues	0.67	4.31	0.40	[28,29]
Livestock	Cattle	Manure	0.84	1.01	0.02	[30]
	Buffalo	Manure	1.42	1.01	0.05	[30]
	Sheep	Manure	0.12	1.31	0.02	[30]
	Goat	Manure	0.13	1.31	0.02	[30]
	Poultry	Manure	0.007	2.43	0.47	[30]
	Pig	Manure	0.11	2.93	0.47	[30]

RPR for agriculture and forestry residue represent unit mass of residue produced per unit mass of biomass product and RPR for livestock represents ton of annually produced volatile solid (VS) mass of manure per animal.

* LHV for agriculture and forestry residue is expressed as MWh/ton of residue and LHV for livestock is expressed as MWh/ton of VS.

Table 3: Assumptions on transport cost, based on [17] **and inflation-adjusted by** [32]

Description	Quantity
Trailer Cost	100,897 USD
Salvage Cost	10 % of trailer cost
Cost Insurance and O&M	8 % of trailer cost
Cost Miscellaneous	4 % of trailer cost
Lifetime	7 years
Annual Distance	80,000 km
Fuel Consumption	34 l / 100 km
Assumed average speed	35 km / h
Assumed Interest Rate	10 %
Maximum transport volume	87.5 m^3
Maximum load	37 t

Table 4: Transport densities and fuel cost of considered biomass residues

Biomass Group	Biomass Type	Biomass Residue	Transport Density [kg/m^3]	Fuel Cost [USD/MWh]	Source
Agriculture	Rice	Straw	190	9.6	[35]
	Rice	Husk	825	8.3	[36]
	Maize	Stalk	190	7.5	[35]
	Maize	Cob	1100	7.0	[37]
	Sugarcane	Bagasse	860	18.1	[38]
	Sugarcane	Top & Leave	190	19.7	[35]
	Oil Palm	Shell	1100	6.8	[39]
	Oil Palm	Fiber	1100	10.5	[39]
	Oil Palm	Empty Fruit Bunches	1100	19.0	[39]
	Oil Palm	Palm Oil Mill Effluent	1000	0.0	Assumed
	Oil Palm	Frond	190	16.9	[35]
	Cassava	Stalk	190	7.9	[35]
	Coconut	Husk	423	7.9	Assumed
	Coconut	Shell	423	7.0	Assumed
	Coconut	Frond	190	9.3	[35]
	Coffee	Husk	423	9.4	Assumed
	Groundnut	Shell	423	10.3	Assumed
	Groundnut	Straw	190	7.7	[35]
Forestry	Industrial Roundwood coniferous	Logging Residues	170	9.2	[35]
	Industrial Roundwood non-coniferous	Logging Residues	170	9.2	[35]
Livestock	Cattle	Manure	800	16.3	Calculated from [40]
	Buffalo	Manure	750	15.6	
	Sheep	Manure	550	13.8	
	Goat	Manure	550	13.3	
	Poultry	Manure	500	50.4	
	Pig	Manure	850	15.8	

Table 5: Process chains and fuel costs of considered biomass residues [35,42]

Residue Group	Residues	Process chain steps	Fuel Costs [USD/ton]	Source
Agricultural Field Based Residues	Rice Straw, Maize Stalk, Sugarcane Top & Leave, Oil Palm Frond, Coconut Frond, Groundnut Straw, Cassava Stalk	Shredding	4.95	[35]
		Raking	2.31	[35]
		Storage and Premium	1.9	[35]
		Farmer Premium	5	Assumed
		Bale Collection	9.78	[35]
		Bale Wrapping	1.73	[35]
		Grinding In-Plant	4.75	[35]
		Receiving	2.22	[35]
		Storing	4.77	[35]
		Total	**37.41**	
Agricultural Process Based Residues	Maize Cob, Sugarcane Bagasse, Oil Palm Shell / Fiber / EFB, Coconut Husk / Shell, Groundnut Shell	Briquetting	22.26	[42]
		Storage and Premium	10	Assumed
		Total	**32.26**	
Forestry Logging Residues	Logging Residues	Piling	2.64	[35]
		Bundling	16.2	[35]
		Receiving	1.1	[35]
		Bundle Grinding	13.04	[35]
		Storing	6.62	[35]
		Total	**39.6**	
Livestock	All livestock manures	Raw Material	5	Assumed
		Receiving and Storing	5	Assumed
		Total	**10**	

Table 6: Available Residual Energy, Max. Electricity Generation and Power Demand in 2013 by country [1,2]

Country	Country Code	Available Residual Energy [TWh]	Max. Electricity Generation [TWh]	Power Demand 2013 [TWh]
Brunei	BN	0.3	0.1	3.2
Cambodia	KH	27.2	9.3	3.3
Indonesia	ID	407.4	131.6	188.4
Laos	LA	13.6	4.7	3.4
Malaysia	MY	68.8	24.1	127.4
Myanmar	MM	95.0	32.1	8.7
Philippines	PH	117.7	39.3	61.6
Singapore	SG	0.1	0.0	45.8
Thailand	TH	193.5	66.1	164.3
Vietnam	VN	152.9	52.4	114.1

Figures:

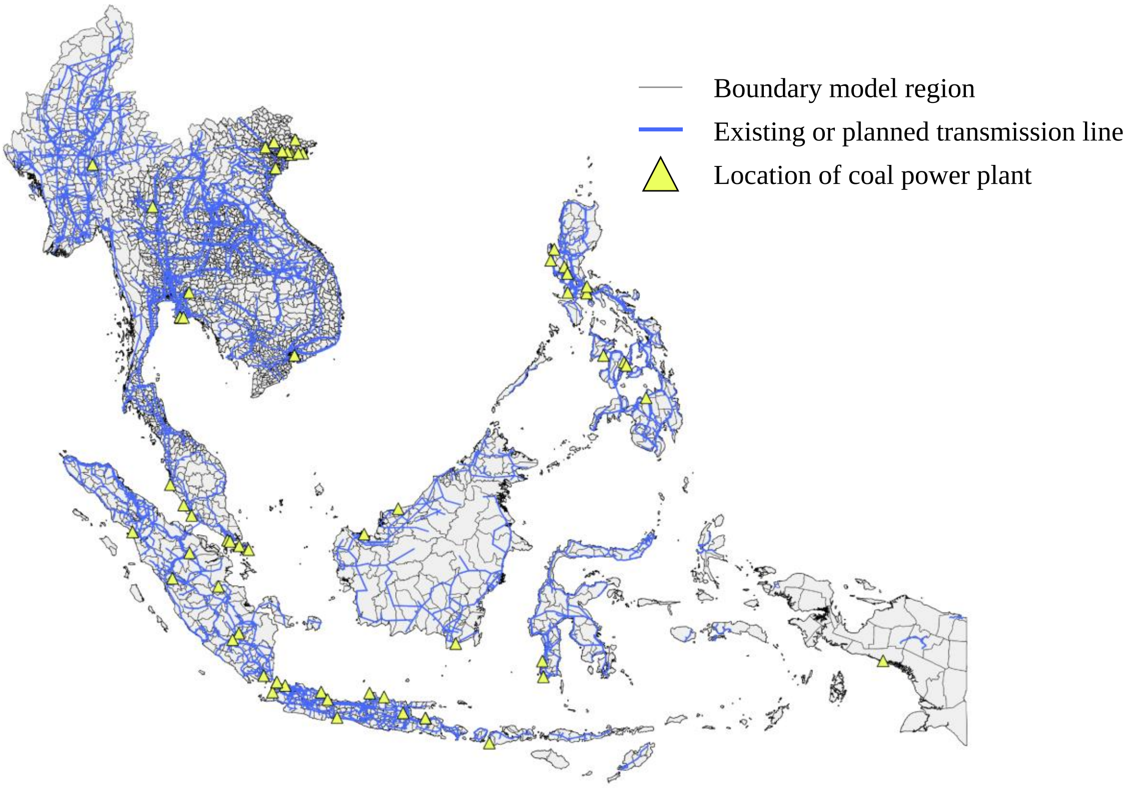

Figure 1: Considered model areas, locations of coal power plants and existing and planned transmission lines

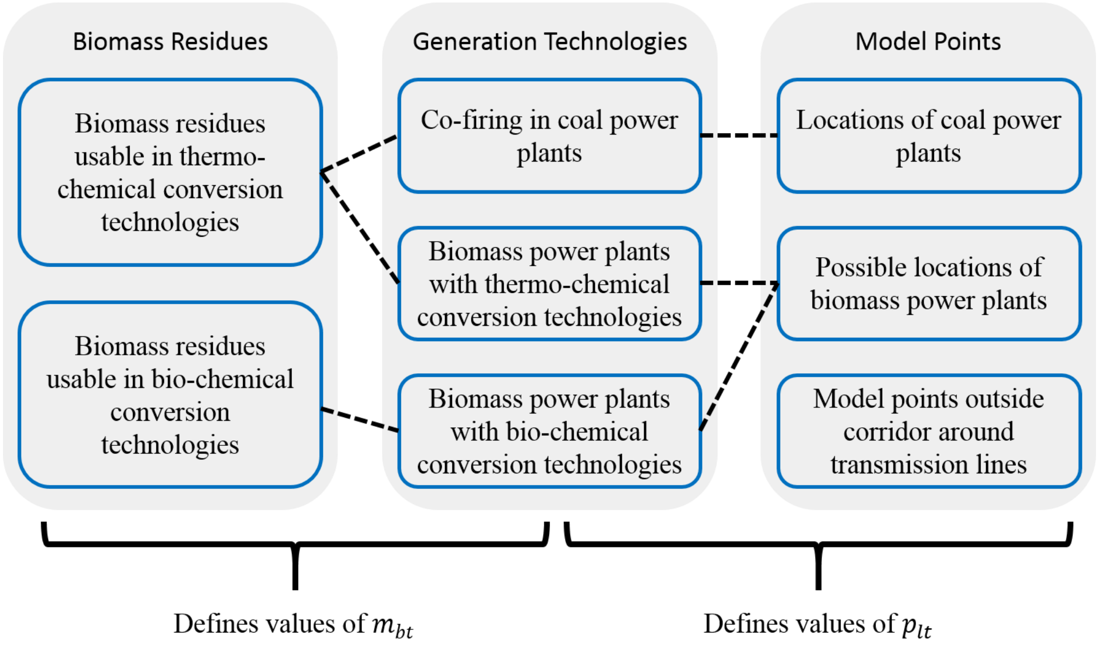

Figure 2: Definition of possible generation options

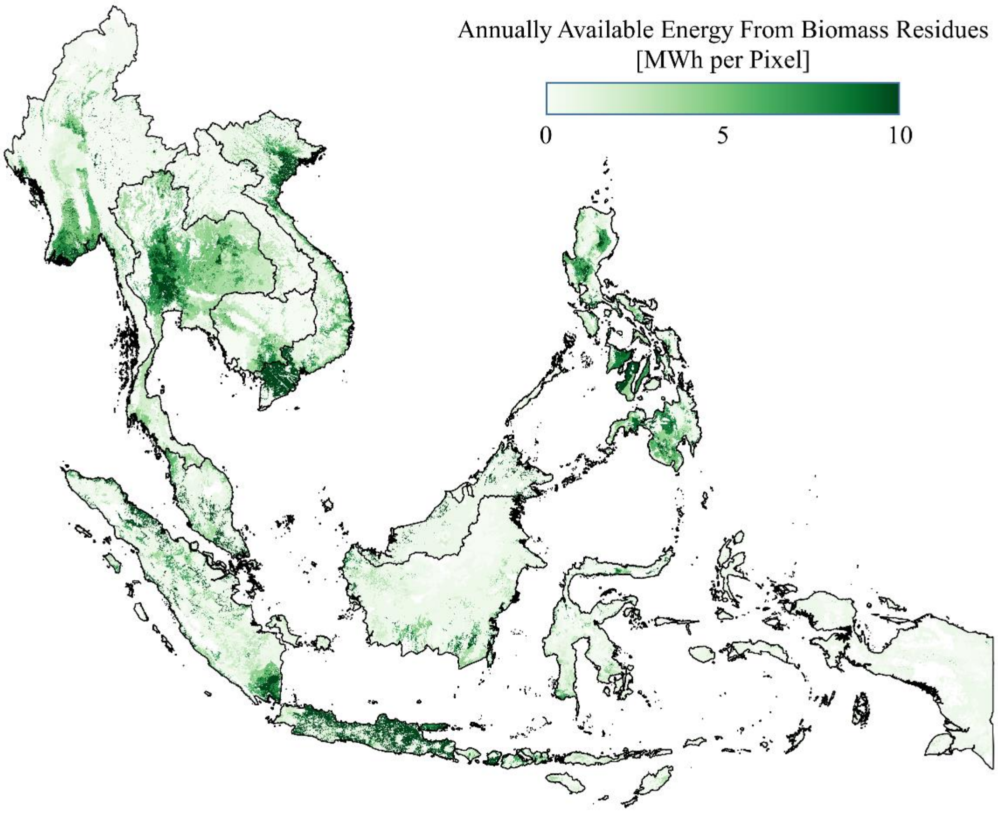

Figure 3: Raster Grid of Total Available Energy from all Biomass Residues

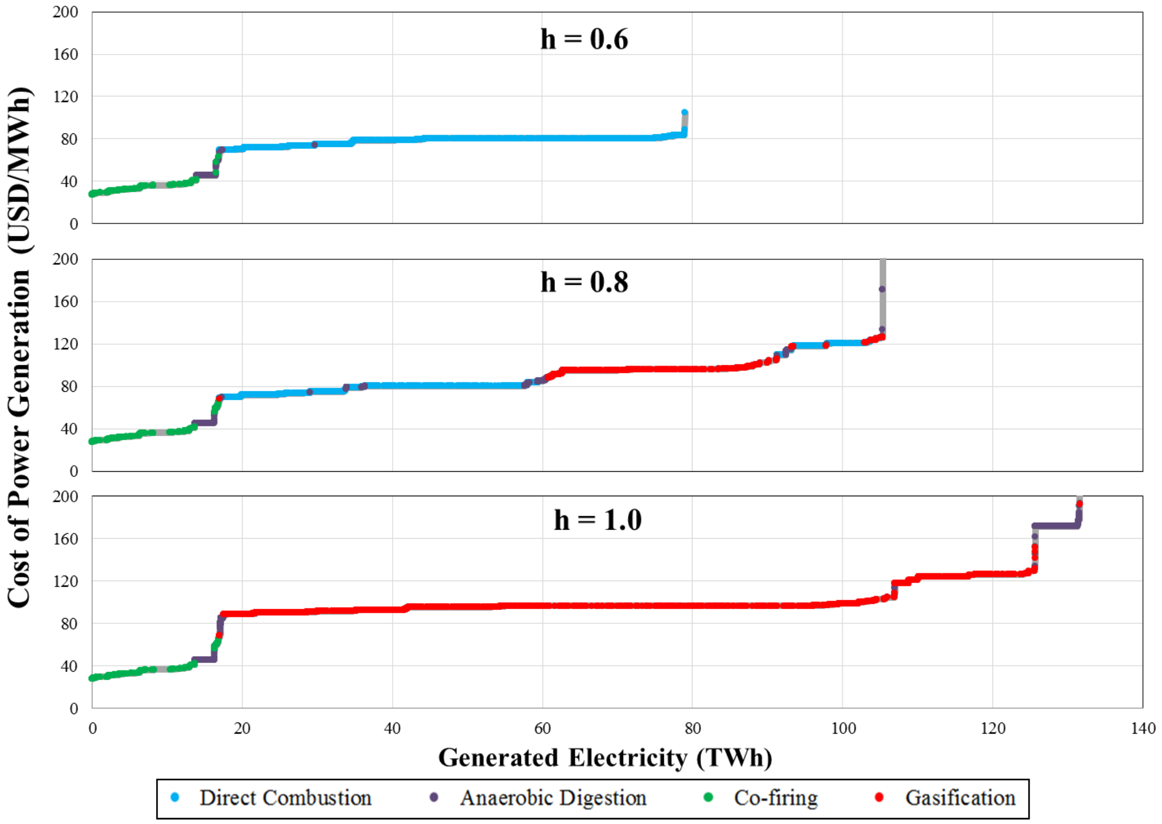

Figure 4: Cost-supply curve of Indonesia with different quantities of generated electricity

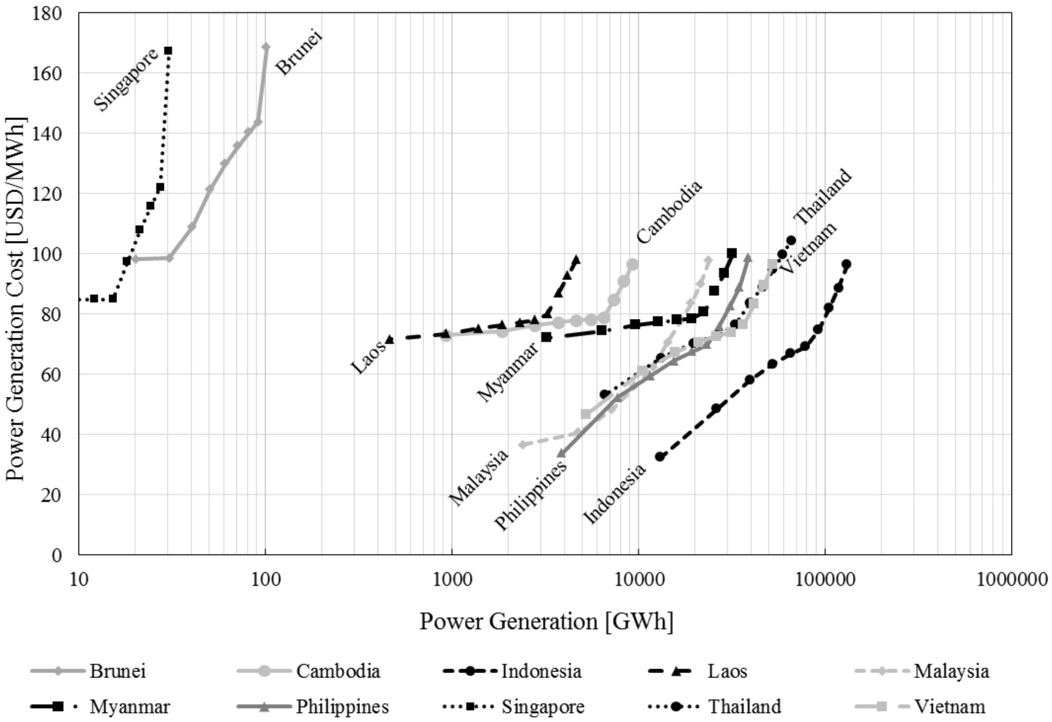

Figure 5: Average power generation costs of each country for different quantities of electricity generated

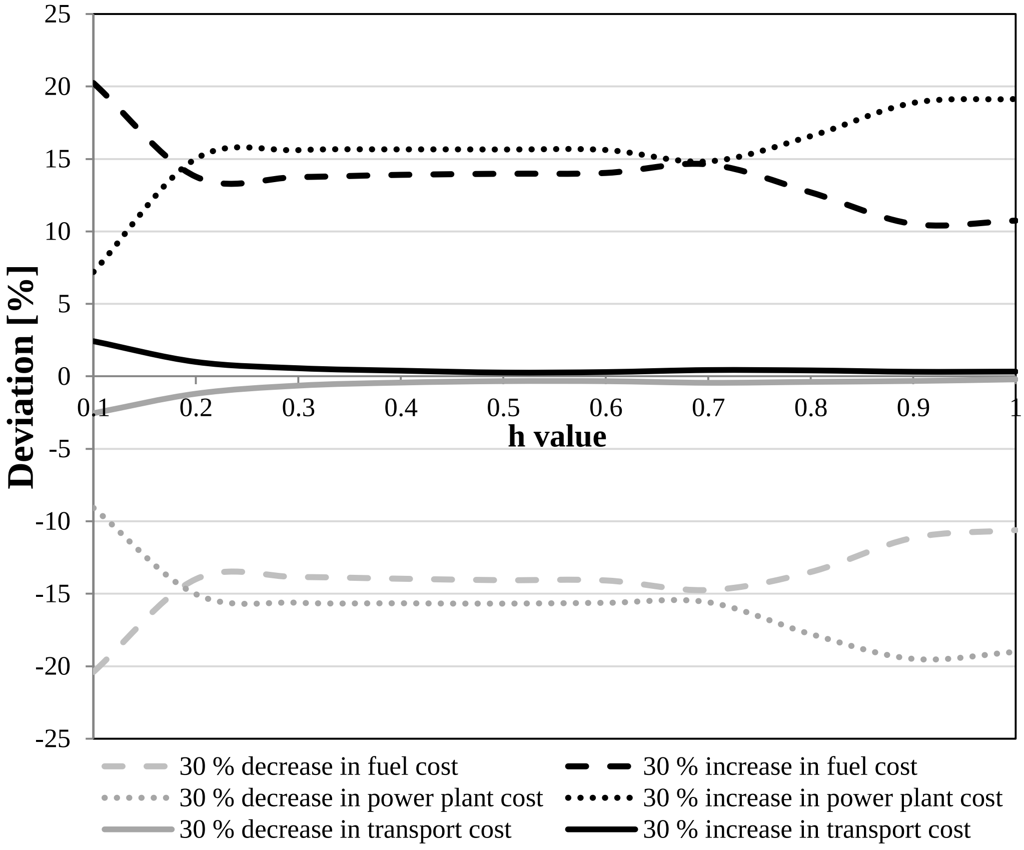

Figure 6: Sensitivity of Indonesia's power generation costs to various input costs

Annex

Table A.1: Number of considered model areas and administrative level by country

Country	No. of areas considered	Administrative Level
Brunei	33	2
Cambodia	184	2
Indonesia	887	2
Laos	142	2
Malaysia	183	2
Myanmar	339	3
Philippines	234	1
Singapore	9	2
Thailand	948	2
Vietnam	697	3

Table A.2: Number of regions for which biomass production data are collected

Biomass Type	BN	KH	ID	LA	MY	MM	PH	SG	TH	VN
Rice	1	24	493	17	14	63	79	1	77	61
Maize	1	24	493	17	14	63	79	1	77	61
Sugarcane	1	24	493	17	14	63	79	1	77	61
Oil Palm	1	1	493	1	14	63	79	1	77	1
Coconut	1	24	493	17	14	63	79	1	77	61
Groundnut	1	24	1	17	14	63	79	1	1	1
Cassava	1	24	493	17	14	1	79	1	77	61
Coconut	1	1	493	1	14	1	79	1	77	61
Coffee	1	1	493	1	14	63	79	1	77	1
Cattle	1	1	497	18	13	1	82	1	77	63
Buffalo	1	1	497	18	13	1	82	1	77	63
Sheep	1	1	497	1	13	1	1	1	1	1
Goat	1	1	497	18	13	1	82	1	1	1
Poultry	1	1	497	18	13	1	1	1	77	63
Pig	1	1	497	18	13	1	82	1	77	63

Table A.3: Available Energy by Residue and Country in [GWh]

	BN	KH	ID	LA	MY	MM	PH	SG	TH	VN	Total
Rice Straw	3.60	18258.33	138599.44	6640.28	5107.82	55935.83	35854.40	0.00	70121.72	85631.96	416153
Rice Husk	0.84	4244.27	32218.34	1543.58	1187.35	13002.65	8334.59	0.00	16300.25	19905.70	96738
Maize Stalk	0.06	1215.14	24265.95	1507.46	115.07	2228.42	9670.12	0.00	6636.52	6804.40	52443
Maize Cob	0.03	717.27	14323.67	889.82	67.92	1315.39	5708.06	0.00	3917.40	4016.49	30956
Sugarcane Bagasse	0.00	55.46	3114.93	109.07	19.78	891.96	2946.15	0.00	9252.00	1860.74	18250
Sugarcane Leave & Top	0.00	338.47	19010.59	665.65	120.71	5443.69	17980.52	0.00	56465.41	11356.20	111381
Oil Palm Shell	0.00	0.00	1438.31	0.00	1147.40	0.00	5.67	0.00	153.56	0.00	2745
Oil Palm EFB	0.00	0.00	26718.00	0.00	21313.97	0.00	105.41	0.00	2852.59	0.00	50990
Oil Palm Fiber	0.00	0.00	6594.14	0.00	5260.40	0.00	26.01	0.00	704.03	0.00	12585
Oil Palm POME	0.00	0.00	8908.37	0.00	7106.55	0.00	35.14	0.00	951.12	0.00	17001
Oil Palm Frond	0.00	0.00	7341.70	0.00	5856.75	0.00	28.96	0.00	783.85	0.00	14011
Cassava Stalk	0.51	1352.25	4046.10	189.32	13.82	106.49	399.00	0.00	5109.49	1649.36	12866
Coconut Husk	0.00	51.05	16105.97	0.00	569.37	374.05	13512.47	0.14	888.91	1147.51	32649
Coconut Shell	0.00	16.06	5066.61	0.00	179.11	117.67	4250.75	0.04	279.63	360.98	10271
Coconut Frond	0.00	42.67	13463.02	0.00	475.94	312.67	11295.11	0.12	743.04	959.20	27292
Coffee Husk	0.00	0.95	1665.58	212.10	39.58	19.66	186.75	0.00	119.16	3481.8	5726
Groundnut Shell / Husk	0.00	30.23	1350.16	48.36	0.65	1385.42	29.31	0.00	47.36	495.73	3387
Groundnut Straw	0.00	111.19	4966.64	177.91	2.39	5096.37	107.82	0.00	174.20	1823.59	12460
Cattle Manure	0.01	49.23	281.93	28.86	13.45	249.56	42.41	0.00	87.40	87.54	840
Buffalo Manure	0.17	48.65	106.80	84.92	8.64	233.89	209.63	0.00	87.73	184.20	965
Pig Manure	0.18	324.45	1244.38	344.07	260.31	1589.05	1787.20	41.05	1184.62	3963.02	10738
Poultry Manure	160.11	177.34	15352.56	278.50	2589.35	1715.97	1444.72	35.39	2389.53	2620.16	26764
Goat Manure	0.02	0.00	62.39	1.51	1.71	13.20	12.41	0.00	1.53	4.63	97
Sheep Manure	0.01	0.00	44.71	0.00	0.39	2.65	0.09	0.00	0.17	0.00	48
Logging Residues	104.72	137.78	61074.77	834.42	17372.47	4955.75	3765.12	0.00	14248.53	6596.12	109090