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Assessment of biomass energy sources and technologies: The case of Central America

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Abstract

This paper reviews and assesses conditions for increased and efficient use of biomass in Central America (CA), providing an overview of conditions for biomass supply in each country. Then, a Fuzzy Multi-Actor Multi-Criteria Decision-Making (MCDM) method is applied to identify a portfolio of biomass conversion technologies appropriate for CA, considering technical, economic, environmental and socio-political aspects. The work is motivated by the relatively large availability of biomass in CA at the same time as current conversion of biomass is carried out in inefficient processes. The assessment of technologies includes thermochemical processes (pyrolysis, combustion and gasification) for production of different energy carriers, including improved cooking stoves (ICSs).

The most promising biomass feedstocks in the region are residue based; animal (manure), forest and agricultural origin. We show that around 250 PJ/year could be available for the energy sector, which represents around 34% of primary energy supply for CA. It is concluded that in the short term promoting and implementing ICSs will give the largest improvement in the efficiency of biomass use, whereas on the long term small combustion plants seems to be the best choice for transforming CA's biomass into a clean and sustainable energy carriers, boosting economy and industrial development. Results show that the introduction of ICSs will result in an annual saving in the range of 4 - 8 Mt of fuelwood (59-113 PJ). Moreover, even when the investment cost of the cooking stoves is considered, ICSs yield economic

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savings to fuelwood consumers compared to traditional stoves. The total savings during the first year of implementation would be in the range of 19 152 US\$/stove.

Keywords: Biomass; Bioenergy; Central America; Multi-Criteria Decision-Making; Technology assessment.

1. Introduction

Since ancient times biomass has played an important role in the CA society, and is nowadays used as fuel in a wide range of applications, such as cooking, heating and power generation. However, due to the growing demand for energy, land area limitations and little investments in new biomass technologies, the use of fossil fuels with their high calorific value have become widely used, making biomass losing importance in spite of recent development of systems for the production of cleaner energy carriers. Currently, all CA countries rely highly on oil imports due to the lack of oil reserves, except Guatemala, which reached an oil production of 3645 Mbbl in 2013 (exporting 88% of the production) ([Torijano, 2011](#)). In Guatemala, there is a form of “natural resource” curse in the sense that the significant resources of oil and hydro have not led to increase in wealth for the average person but merely contributed to corruption and highly unevenly distributed incomes ([Mehlum et al., 2006](#)). According to data reported by [Transparency International \(2013\)](#), which ranks 175 countries on scale from 0 (highly corrupt) to 100 (very clean), CA countries are ranked among the highly corrupt countries in the world, especially Guatemala and Honduras, which are placed at 129th and 140th position. Only Costa Rica has been ranked among the top 50 countries that are considered to operate with a high level of transparency.

In recent years, there has been an increased interest in biomass as a renewable feedstock worldwide due to increased cost of petroleum products, security supply and the growing awareness of climate change. Increases in the price of oil can have a more profound effect on developing countries than developed ones since the economy in developing regions relies on that economic sources are sourced to important areas for improvement (food, jobs, security, etc.). According to data reported by the [World Bank Database \(2014\)](#), 37% of CA’s population lives below the poverty line.

Furthermore, in recent years there has been an increased concern in the region over the shift of the economic base from agricultural exports towards the manufacturing and tourism sectors, which has resulted in increased pollution and greenhouse gas (GHG) emissions due to the high oil consumption

in these sectors (Apergis and Payne, 2011). According to data reported by Torijano (2011), the ratio of imports over consumption of petroleum products in the region increased by 20% in the period 2005-2013. With respect to regional GHG emissions, these have increased by 35% during the period 2000-2010, with the highest increase in Panama; around 66% during this period (CEPAL, 2014).

The aim of this paper is to make an assessment of the potential in biomass resources available in CA and discuss this potential with respect to the expected long-term energy needs of the region. Based on this assessment, the paper then evaluates the technologies that could be used to efficiently realize the biomass potential by application of different technologies (combustion, pyrolysis and gasification) for conversion of bioenergy into different energy carriers. The technologies included are such which are considered the main near term options under development offering the highest conversion efficiencies and lowest technical complexity considering CA's conditions.

The paper is organized as follows: *Section 2* gives a brief outline of the methodology used for mapping of biomass resources and technology assessment. *Section 3* discusses the current demand and energy matrix of CA. *Section 4* presents an assessment of the potential biomass resources available in CA. *Section 5* discusses the potential technologies that could be used to transform CA's biomass into energy carriers and *Section 6* provides a ranking of technologies based on an MCDM method. Finally, *Section 7* concludes the work and proposes future work.

2. Materials and Methods

This work comprises Central America: Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama. This subsection is divided in two parts, the first subsection (*section 2.1*) focuses on describing the approach used to assess the potential in biomass resources available in CA, while *section 2.2* describes the methodology used to identify if technologies based on thermochemical processes are feasible under CA conditions. Although some biomass feedstock (i.e., animal origin) mentioned in *section 2.1* could be transformed more efficiently through anaerobic processes, these were not analyzed with the methodology presented in *section 2.2* since they do not share a common base (biomass properties, e.g., moisture) with thermochemical processes. High-moisture content feedstocks require time and energy consuming operations (e.g., drying) for the biomass to fulfill the requirements of the conversion process. This makes the thermochemical route

less attractive and costly compared to anaerobic systems. Therefore, this study excludes the anaerobic processes from the technology assessment as it is considered that thermochemical processes will only be employed for low moisture content feedstocks ($\leq 50\%$ moisture). On the other hand, despite the fact that improved cooking stoves (ICSs) can only produce domestic heat, they are included in *section 2.2*, since they are of low complexity and well suited for short-term application in CA.

Finally, this study presents the potential electricity production that could be obtained if all potential residues generated from forestry and forest sector (estimated based on the methodology presented in *section 2.1*) were combusted or gasified. The four configurations under analysis are downdraft gasifier/gas engine (DG/GE), fluidized bed gasifier/gas engine (FB/GE), grate firing/steam cycle (GF/ST) and circulating fluidized bed combustor/steam cycle (CFB/ST). It is assumed that the average lower heating value (LHV) of logging residues on wet basis (w.b.) is 8 MJ kg^{-1} , while for the processing residues, it is assumed an average LHV (w.b.) of 10.5 MJ kg^{-1} . For the DG/GE, FB/GE, GF/ST and CFB/ST configurations it was considered an overall efficiency (Dornburg and Faaij, 2001) of conversion to electricity of 18%, 33%, 27% and 29%, respectively, was considered.

2.1. Biomass resources potential

As far as possible, the most recent regional statistics data have been gathered from available sources to assess the biomass potential for CA countries. The types of biomass feedstock under study have been classified into three categories: animal, forest and agricultural. The FAO Database (FAO, 2014) concerning livestock, forestry products and processed crops are used as a starting point for the calculation of biomass potential. It is important to mention that this paper does not propose to use old growth forests to produce energy carriers but forest residues from the forestry and forest industry.

With respect to biomass from animal origin, two of the most representative livestock species in the region are taken as an example, i.e., cattle and swine stock. In order to estimate the manure produced from these species, a cattle manure (CM) average yield of 23.4 kg day^{-1} and a swine manure (PM) average yield of 1.1 kg day^{-1} are assumed (Monteiro et al., 2011). With respect to the potential biogas production from cattle manure, the following average composition was assumed (Monteiro et al., 2011): total solids (TS) 8.5%, volatile solids 76.5% of TS and a biogas yield $0.23 \text{ Mm}^3 \text{ year}^{-1}$. The corresponding average figures for potential biogas production from pigs

manure are (Monteiro et al., 2011): total solids (TS) 6.1%, volatile solids 72.5% of TS and a biogas yield of $0.35 \text{ Mm}^3 \text{ year}^{-1}$. In order to obtain the biogas production, the number of cattle or swine has to be multiplied by the manure yield, total solids content, volatile solids content and biogas yield. With respect to the electricity or heat production, the biogas production has to be multiplied by the LHV of biogas and electrical/thermal efficiency. The LHV of biogas was set at 6 kWh/m^3 . An electrical efficiency of 30% and a thermal efficiency of 60% were assumed.

With respect to biomass from forest origin, this essentially comes from two forestry products, i.e., fuelwood and industrial roundwood. The data on fuelwood and industrial roundwood production were obtained from FAO (2011). The residues generated by the forest industry with respect to the aforementioned products can be divided in two groups: (1) logging residues as a result of logging operations and (2) wood processing residues as a result of transforming industrial roundwood into timber, sawn wood, plywood, and paper, among others. The amount of wood logging residues is calculated multiplying the production of fuelwood and industrial roundwood by the logging residue generation ratio, which is set to 0.60 (Parikka, 2004), meaning that 60% of the total harvested tree is left in the forest. The amount of wood processing residues is calculated by multiplying the production of industrial roundwood by the wood processing residue generation ratio, which is set to 0.50 (Smeets and Faaij, 2007). As all these residues cannot be recovered in full due to their scattered nature (which makes the collection process challenging and even not feasible), a recoverability fraction for logging residues and wood processing residues was set to be 25% and 75%, respectively. This parameter also takes into account the alternative uses of these residues for animal bedding and protection against soil depletion. The inclusion of all these parameters (i.e., residue generation ratios and recoverability fractions) into the calculation prevents overestimating the bioenergy production potential. To estimate the energy contained in these residues (Wood Energy, 2015), the LHV (w.b.) of logging residues was assumed to be 8 MJ kg^{-1} and the LHV (w.b.) of wood processing residues was set at 10.5 MJ kg^{-1} .

With respect to biomass from agricultural origin, the amount of residues from agricultural activities (from harvesting to final product) is calculated multiplying the production of the i_{th} crop by the corresponding residue product ratio (RPR). Table 1 presents values for RPR and LHV for different agricultural residues.

Due to the fact that not all agricultural residues can be extracted from the fields because of scattered abundance, the demand for other ecosystem services and other uses (e.g., fertilizer), a sustainable extraction rate has

been set to 25% in accordance to (Eisentraut, 2010).

[Table 1 about here.]

2.2. Technology Assessment

When selecting a technology with respect to a biomass conversion process, several variables have to be considered, e.g., resource availability, state of technology and market availability. Facilities processing biomass through thermochemical processes (direct combustion, gasification and pyrolysis) to produce fuels, power, heat and chemicals are here denoted biorefineries. As mentioned above, the anaerobic processes are not included in the analysis. Figure 1 gives a schematic chart of the technology assessment applied in this work, including the criteria and the interactions between the different blocks.

[Figure 1 about here.]

As can be seen in Figure 1, the assessment considers seven blocks: biomass resource, technology, flexibility (ability to produce more than one product/energy carrier), biorefinery, products-market, costs and policies. Each block in Figure 1 contains the criteria (C) taking into consideration for the technology assessment performed in this study. Note that no block in Figure 1 deal with the size of the plant as this is mainly determined by the availability of biomass and commercial equipment for large-scale production (e.g., boiler or gasifier) and handling of biomass supply. Thus, instead, interactions regarding to scale/capacity are considered by the criteria “scale of operation” part of the technology block.

Also, as can be observed, a special characteristic of the system presented in Figure 1 is that considers criteria (e.g. climate conditions, state of technology and complexity) which are typically difficult to compare quantitatively. Thus, a Fuzzy Multi-Criteria Decision-Making method has been used to rank future biomass-based technologies under CA conditions taking into account multiple conflicting criteria defining the seven blocks. Multi-Criteria Decision-Making methods have been prove to be a useful tool for assisting decision making with multiple objectives (Chen et al., 2011). In this case, by using fuzzy sets, decision-makers are not required to explicitly define a measurement scale (crisp value) for each attribute, which makes the judgment process easier when facing heterogeneous criteria (of both qualitative and quantitative nature) (Chen et al., 2011). Fuzzy sets were introduced by Zadeh (1965) to handle problems in which a source of uncertainty is involved. Fuzzy sets are defined mathematically by a membership function

$\mu_a(X)$, which associates each element x of the space X a real number in the interval $[0,1]$ (Chaghooshi et al., 2012). The MCDM methodology used in this study is based on fuzzy triangular numbers Ren et al. (2013). The triangular fuzzy number $\mu_a(x, a^l, a^m, a^u)$ is defined as:

$$\mu_a(x, a^l, a^m, a^u) = \begin{cases} a^l \leq x \leq a^m & \frac{x-a^l}{a^m-a^l} \\ a^m \leq x \leq a^u & \frac{a^u-x}{a^u-a^m} \\ x > a^u \text{ or } x < a^l, & 0 \end{cases} \quad (1)$$

From here on, each of the blocks of the system presented in Figure 1 and its corresponding criteria are going to be described.

The *biomass resource* block takes into account parameters such as biomass availability, biomass properties and climate conditions. *Biomass availability* criterion measures if there is enough supply of biomass to supply the processing plant during its entire life. With respect to the *biomass properties* criterion, two biomass properties are crucial when selecting between thermochemical processes, i.e., moisture and ash/alkali content. These criteria measure in which extent the properties of biomass influence the performance of a technology. *Climate conditions* criterion measures the influence of weather seasons on the biorefinery operation and the challenge to implement systems that enable the biorefinery to operate despite the weather conditions. For the analysis of the CA region, this is a highly important factor due to the heavy rains, which can limit biomass transportation to the biorefinery.

The *biorefinery* block takes into consideration biomass pre-treatment, cleaning systems, generation of non-ash residues from the conversion process, process efficiency, personnel competence, manufacturing equipment and engineering companies. The *biomass pre-treatment* criterion is dependent on the biomass properties (moisture, size and shape) and climate conditions, e.g., some reactors are only able to process biomass under certain moisture content and homogeneous size and shape. With respect to the *cleaning systems* criterion, this measures the challenge of implementing efficient cleaning systems based on the process requirements (conversion unit), biomass pre-treatment and environmental regulation. The *residues* criterion measures the complexity of dealing with the non-ash residues resulting from the conversion process. The *process efficiency* criterion is defined as the energy efficiency to total products and services. This criterion measures the challenge to improve process efficiency by improvements of biomass yields, reuse of waste streams, improve process control, reducing complexity of the process, access to new commercial systems and process integration. This

criterion also takes into account the possible co-feeding, use of secondary feedstock and the import/export of heat and power. The *personnel competence* criterion measures the challenge to find/hire high-skilled personnel to manage, operate and control all parts of the biorefinery. The *manufacturing equipment* criterion refers to the existence of local manufacturers of units based on biomass technologies. The *engineering companies* criterion refers to the existence of local engineering companies (e.g., technical consultancies, specialist services, etc.) capable of designing and providing technical support to the biorefinery.

The *technology* block measures the uncertainty about the availability of commercial equipment capable of processing the desired biomass. The *state of technology* criterion measures the degree of maturity of a technology. The *scale of operation* criterion measures if the scale of the plant equipment under analysis matches the scale of commercial operation. The *complexity* criterion evaluates the complexity of the different processing technologies (comparing to equivalent fossil fuels) in the biorefinery (e.g., biomass pre-treatment, gas cleaning, trained personnel and energy storage, among others) as well as the logistics.

The *cost* block takes into consideration the investment cost of the technology. The *investment* criterion measure how expensive is implementing the technology compared to other renewable or non-renewable technologies.

The *products-market* block takes into account the market interactions. The *market availability* criterion measures if there is a market available where to sell the products resulting from the conversion process. The *market stability* criterion measures the price stability of equipment/materials related with the construction process (e.g., steel price), operation (e.g., oil price) and end-product.

The *flexibility* block takes into consideration parameters such as poly-generation and versatility. The *polygeneration* criterion measures if the conversion process is able to produce more than one product or if the final product can be later upgraded. The *versatility* criterion refers to the degree of flexibility of a technology to process different types of biomass (as well as heterogeneous biomass) and to what extent it can be integrated in a system with other technologies (e.g., power to gas).

The *policies* block measures the environmental impact of the conversion process (e.g., GHG emissions) and to what extent it can be integrated in a system with other technologies to reduce CO₂ emissions (e.g., carbon capture and storage). This part also takes into consideration if there is any kind of incentive/subsidy promoting the technology and if there is any regulation regarding manufacturer's warranty (or how challenging it would be to obtain

plant level guarantees).

Four technologies have been analyzed with this methodology: combustion (BC); gasification (BG); pyrolysis (BP) and improved cooking stoves (ICSs). Here, BC refers to using a solid fuel for heat and power generation; while in ICSs a solid fuel is directly combusted only for heat generation. Furthermore, as this work has been developed as a joint project between three different institutions (decision-making groups), the Fuzzy Multi-Criteria Decision-Making method has been extended to a Fuzzy Multi-Actor Multi-Criteria Decision-Making (MCDM) method (Ren et al., 2013). This is because a MCDM analysis allows including the choices of several decision-making groups using linguistic assessment. It has been set that each decision-making group is formed by each of the authors involved in this work, each one from a different institution, i.e., Group 1 - *Carlos III University of Madrid*, Group 2 - *AICIA* and Group 3 - *Chalmers University of Technology*.

The first step of the MCDM method is that each decision-making group L will compare each alternative (technology, T) by fuzzy linguistic assessment variable for a set of criteria C . That is, firstly, decision makers rate all 22 conflicting criteria with respect to importance (e.g., lower or higher) in the energy system defined in Figure 1. Secondly, the decision-makers judge the performance (e.g., worse or better) of each alternative on each of the 22 criteria selected to assess the technologies considered in the analysis (BC, BG, BP and ICSs). Then, the choices of each decision-making group L are gathered in a matrix DM , which is then transformed into fuzzy triangular numbers to carry out the technology assessment. Table 2 shows the linguistic variables employed to address the importance (I) of each criteria C and the performance (x) of each technology under each of the 22 criteria presented in Figure 1, as well as the fuzzy scale corresponding to each linguistic variable.

[Table 2 about here.]

After transforming matrix DM into fuzzy triangular numbers, the resultant

matrix A_k of each decision group L can be arranged in the following form:

$$A_k = \begin{bmatrix} & T_i & T_2 & & \dots & T_n \\ C_j & \hat{I}_j & \hat{x}_{ij} & \hat{x}_{12} & \dots & \hat{x}_{1n} \\ C_2 & \hat{I}_2 & \hat{x}_{21} & \hat{x}_{22} & \dots & \hat{x}_{2n} \\ & L & M & R & & \\ & (0.3, 0.5, 0.7) & & (0.7, 0.9, 1.0) & & \vdots \\ C_m & \hat{I}_m & \hat{x}_{m1} & \hat{x}_{m2} & \dots & \hat{x}_{mn} \end{bmatrix}^k \quad (2)$$

Where, T_i represents the i_{th} technology; C_j the j_{th} criterion; $\hat{I}_j$ the weight of the j_{th} criterion by the k_{th} decision-making group and $\hat{x}_{ij}$ is defined as the performance of the j_{th} criterion corresponding to the i_{th} technology by the k_{th} decision-making group.

Once all the L matrices A_k have been obtained, the average multi-criteria decision matrix $\bar{A}_k(\bar{x}_{ij}, \bar{w}_j)$ is calculated. This matrix contains the average of all decisions matrices A_k . Now that $\bar{A}_k$ is determined, we proceed to normalize the weights of the criteria.

$$x_{ij} = \frac{\bar{x}_{ij}^L + 2\bar{x}_{ij}^M + \bar{x}_{ij}^R}{4} \quad (3)$$

$$I_j = \frac{I_j^o}{\sum_{j=1}^n \bar{I}^o} \quad (4)$$

$$I_j^o = \frac{\bar{I}_j^L + 2\bar{I}_j^M + \bar{I}_j^R}{4} \quad (5)$$

After matrix $\bar{A}_k$ is normalized, we obtain a matrix that no longer has fuzzy triangular numbers, all elements inside the matrix are crisp values. In order to rank the technologies corresponding to each criterion, for the j_{th} criterion, we apply the following fuzzy linear 0-1 programming to x_{ij} :

$$\varphi_{it}^j = \begin{cases} 1, & \text{if the alternative has been ranked in the } t_{th} \text{ place} \\ 0, & \text{if the alternative has not been ranked in the } t_{th} \text{ place} \end{cases} \quad (6)$$

$$\varphi^j = \left\{ \varphi_{it}^j \right\}_{m \times m} \quad (7)$$

Where, φ^j is the ranking matrix corresponding to the j_{th} criterion. φ_{it}^j is the element corresponding to the j_{th} criterion. This procedure is performed until the m matrices C are built for all criteria. Then, the weighted ranking matrix R is obtained by the following expression:

$$R = \sum_{j=1}^m C_j I_j \quad (8)$$

Finally, to rank the sequence of technologies and calculate the final ranking matrix, a fuzzy linear 0-1 programming is used:

$$z_{it} = \begin{cases} 1, & \text{if the alternative has been ranked in the } t_{th} \text{ place} \\ 0, & \text{if the alternative has not been ranked in the } t_{th} \text{ place} \end{cases} \quad (9)$$

$$z^j = \{z_{it}\}_{m \times m} \quad (10)$$

Where, Z is the final ranking matrix and z_{it} represents the t_{th} position of the i_{th} technology inside the Z matrix. For example, for a technology assessment with a final ranking matrix Z , the following form is obtained:

$$Z = \begin{bmatrix} T_1 & 0 & 1^{2nd} & \dots & 0 \\ T_2 & 1^{1st} & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ T_N & 0 & 1 & \dots & 0 \end{bmatrix} \quad (11)$$

A higher-ranking value indicates an alternative with higher priority. That is, the non-zero value in the first column of matrix Z will indicate that the technology # 2 is the best alternative for the case study.

3. Central America's energy demand

Renewable resources in CA have always been an important part of the region's energy portfolio. However, due to the weak energy policy, low-quality institutions and lack of investment these resources have never been fully exploited and development of the sector has mostly stayed at paper studies. The latter can be seen from the small amount of economic resources that CA countries have been investing in research and development (R&D) projects over the last years. Based on data reported by the [World Bank Database \(2014\)](#), in 2009, CA countries, on average, spent only 0.22% of their GDP in R&D. Meanwhile, for the same year, countries such as Finland,

Sweden and Denmark spent 3.93, 3.60 and 3.06% of their GDP. Among the CA countries, Costa Rica was the country that invested the most in R&D projects, around 0.54% of the GDP ([World Bank Database, 2014](#)). Ratios for Guatemala and El Salvador were less than 0.1%. From these data, it can be inferred that technology development is still low on the political agenda in CA.

[Figure 2 about here.]

In 2009, the top energy consuming sectors in CA were the residential and transport sectors, accounting together for 72% ([OLADE, 2009](#)) of regional energy consumption. The energy consumption of the residential sector was reported to be 40% ([OLADE, 2009](#)) of the region's energy consumption, of which more than 80% is supplied by fuelwood (Figure 2). Meanwhile, the transport sector is dominated by gasoline and diesel (Figure 2) and accounts for 32% ([OLADE, 2009](#)) of regional energy consumption.

The energy consumption in the industrial sector is more diversified. This sector mainly consumes diesel and electricity, accounting for 19% and 18% of the energy use, respectively. With respect to electricity consumption, it is important to highlight that residential and commercial sectors account for 71% of the total electricity consumption. In all, fossil fuels provide about 35% of the total electricity supply in CA with 78% of the fossil based electricity generated in diesel and fuel oil generators ([CEPAL, 2014](#)) with low conversion efficiency.

If CA's energy mix is analyzed based on the percentage of renewable energy resources (RES) contributing to energy supply, the region can be divided into two groups: low-RES users and high-RES users. Among the low-RES users ([CEPAL, 2014](#)) are Guatemala and Panama, where around 84% and 83% of total energy supply comes from non-renewable resources, respectively. In other CA countries ([CEPAL, 2014](#)), supply from renewables exceed 40%, with 51% in Costa Rica, 49% in El Salvador, 45% in Honduras and 49% in Nicaragua. Costa Rica, with the highest share, has one of the most diversified renewable matrices in the region, where around 30 MW come from biomass and waste ([MIF/BNEF, 2013](#)) while the remaining is mainly electricity from small hydro (588 MW, which is equivalent to 60% of Costa Rica's renewable energy share).

When it comes to RES, the highest potential is in biomass but currently in the region the most exploited RES is hydro. In 2011, biomass consumption for CA was reported to be 11 472 Mtoe ([CEPAL, 2014](#)), which is equivalent to 69% of the total supply of renewable energy. Most of this

consumption was used for thermal purposes (domestic cooking and heating) through low efficient technologies.

[Figure 3 about here.]

Generally, fuelwood constitutes the main fuel in the urban and rural households in CA (Figure 3). According to ECLAC (2010), there are 18 million people who depend on fuelwood in Guatemala, Honduras and Nicaragua. Based on data reported by (CEPAL, 2014), in 2011, about 5295 and 1674 Mtoe of fuelwood were consumed in Guatemala and Honduras, respectively, accounting together for 60% of the regional biomass consumption. The main challenges in switching from firewood to modern energy carriers (e.g., electricity) in developing countries are high up-front cost of the technology, the geographic distribution of the households and infrastructure of the biomass supply logistics. Even if a technology provides clear economic and health benefits it is not straightforward to determine what is required for households to adopt the technology in the short term. High up-front cost of technologies is one of the greatest hurdles in dissemination of renewable energy technologies, especially in developing countries where low-income households dominate. Therefore, economic incentives such as micro-loans and investments subsidies are crucial for successful deployment of such new technologies. Furthermore, the geographical distribution of households in rural regions makes it difficult and expensive to connect households to the grid. Considering that for biomass fuelled systems the production cost of the energy carrier (e.g., electricity) strongly depends on the cost of the biomass fuel and that the dominant fuel resource in the CA region is forest-derived biomass, the implementation of small/medium scale energy systems based on the use of local resources could be a good opportunity to meet household's energy demand, avoiding costly logistical practices. A study by Allen et al. (1998) indicates that biomass harvesting, storage, transport, pre-treatment and delivery account for 20-50% of the total costs of end product (e.g., electricity). Obviously, biomass-based energy systems also require the development of infrastructure capable of handling, processing and delivering energy carriers both with respect to the fuel supply and the end product (e.g., electricity, transportation fuel). This goes from the construction of roads to transport any item related to the energy system for the creation of mini-grids to supply electricity.

Biomass that is not used for thermal purposes is transformed to produce energy carriers such as process steam and power. According to data reported by the MIF/BNEF (2013), the current installed capacity of biomass plants in

CA is 672 MW. The country with highest installed capacity in the region is Guatemala with 330 MW. It is important to highlight that currently there are no plants producing electricity from biomass in Panama. Panama’s electricity is mainly supplied by large hydro (44%) and diesel (43%) plants (MIF/BNEF, 2013).

Besides fuelwood, the second most important biomass resource is sugarcane by-products (bagasse and molasses), which account for 13% of the biomass share in CA (Figure 3). Although this share may seem small, these are the only residues that are currently used to produce energy carriers at large scale with the available technologies in the region. The sugar industry uses sugarcane bagasse to produce electricity in Combined Heat and Power Plants (CHP), and ethanol from molasses in distilleries.

In summary it can be concluded that although there has been a significant increase in the installed capacity for biomass conversion units in CA, there is obviously still significant potential for improvement in technology for increased conversion efficiency as well as increase in the use of biomass from domestic resources in order to reduce fossil fuel dependence.

4. Central America’s biomass resources

4.1. Animal origin

Animal origin refers to all organic residues from livestock (cattle, pigs, chickens, etc.), i.e., animal manure. Manure can be converted into biogas through anaerobic digestion in a “biodigester”. The conversion reaction produces carbon dioxide (CO_2) and methane (CH_4). Biogas consists of 55-80% CH_4 , 20-45% CO_2 and traces of H_2S and other impurities (Truong and Abatzoglou, 2005).

The product gas from the digestion process must be cleaned in order to remove solids, water and corrosive compounds (e.g., sulfur) and then combusted in internal combustion engines (ICEs) to produce heat and power but it is also possible to use the product gas as transportation fuel if upgraded (CO_2 and S removal) as well as it can be used in especially designed lanterns and stoves.

One of the main benefits of this technology is that energy carriers can be produced without affecting the manure nutrients, which later on can be re-incorporated to the soil and used as a fertilizer depending on the local environmental legislation with respect to the minimum pathogen-kill standards. For example, based on data reported by CONAMA (2006) in order to use the digestate on agricultural fields, this residue must have the following characteristics: thermotolerant coliforms $< 10^3$ MPN/g TS, < 0.25

helminth viable ova/g TS, total absence of salmonella in 10 g TS and < 0.25 enterovirus/g TS. To achieve these conditions a pasteurization stage might be required in the process prior anaerobic digestion.

The production of biogas is limited to farmed animals. This, in order to have an efficient system for collection, handling and transporting of manure. Transporting animal wastes over long distances will significantly increase the production cost of biogas, making this process less attractive for investors. Digesters for small biogas production can range from 12 to 100 m³ and their cost vary from US\$ 675 to US\$ 4000 for the aforementioned capacities (Lim-meechokchai and Chawana, 2007). The regional price of a biodigester of 12 m³ capacity, which is equivalent to 10 cooking hours (burner consumption: 0.4 m³ h⁻¹ (Q Energy Consultants, 2015)), is around US\$ 1900 (Biogas Nicaragua, 2015). Although this investment may not seem large considering that a high-value product is obtained, spending this amount of money may represent an issue for low-income farmers. To set this value in context, the average minimum wage in CA is about 300 US\$/month (Quandl, 2015), which clearly shows that a part of the population will struggle accessing this type of technology unless there is some economic support policies. The possibility of installing digesters between neighboring farms or community biodigesters could be a good alternative to implement these systems. In this way farmers and households could share the investment and maintenance cost of the plant.

Currently, in CA, biogas is commonly produced from animal manure. Figure 4 presents the cattle and swine stock for CA (around 18 million), as well as the manure production from both species based on assumptions made in *section 2.1*.

[Figure 4 about here.]

It is estimated that 327 kt day⁻¹ of cattle manure (CM) and 5 kt day⁻¹ of swine manure (PM) were produced in CA during 2011. Guatemala and Nicaragua account for 51% of total manure production.

Figure 5 shows the potential biogas production in the region. Two case studies have been evaluated, i.e., biogas from CM and biogas from PM.

[Figure 5 about here.]

As can be seen from Figure 5a and Figure 5b, the potential biogas production in the region is $1817 \text{ Mm}^3 \text{ year}^{-1}$ (39 PJ). If biogas is used for CHP applications, the region could produce $3270 \text{ GWh year}^{-1}$ of electricity (Figure 5c) and $6541 \text{ GWh year}^{-1}$ of heat (Figure 5d). Since the most valuable energy carriers for the region are heat and power we have limited the analysis to these energy carriers. It is important to mention that although the large potential of animal origin biomass is already acknowledged among decision makers in CA, the production of biogas fuel has not yet been fully exploited.

4.2. Forest origin

The forests in CA constitute an important biomass asset and cover 38% of the region's total land area.

[Figure 6 about here.]

In countries like Belize and Costa Rica, the forests cover more than half of the land area: 61% and 51% respectively (Figure 6). However, it is important to point out that these values also include forest designated primarily for conservation of biodiversity (47% of forest area) and for protection of soil and water (9% of forest area).

Estimates from FAO (2010) indicate that in 2010, around 19% ($3613 \cdot 10^3 \text{ ha}$) of the CA forests were available for biomass production but only 42% FAO (2011) of these forests are designated for production ($1522 \cdot 10^3 \text{ ha}$). Data reported by FAO (2010) regarding the area of forest designated for production makes no distinction between native and planted forests. Nonetheless, it is known that the area of planted forests corresponds to 3% ($584 \cdot 10^3 \text{ ha}$) of total forests in CA.

Figure 7 shows the production, imports and consumption of several products coming from CA forests.

[Figure 7 about here.]

Data presented in Figure 7 show that the production of fuelwood (FW), industrial roundwood (IR) and sawnwood reached $46\,003 (10^3) \text{ m}^3$ in 2011, where fuelwood accounted for 88% of this production. The top fuelwood consumers are Guatemala (43%), Honduras (21%) and Nicaragua (15%), accounting for 79% of regional consumption (Figure 7). As mentioned in section 3, most of the fuelwood consumed in CA is used for domestic cooking and space heating. This biomass is burned inefficiently in open fire stoves at an estimated energy efficiency of 5%-17% (Berrueta et al., 2008). Thus,

there is a great potential to improve energy efficiency in the use of forest biomass by using state-of-the-art technologies, i.e., by using ICSs or larger plants for generation of both heat and power.

With respect to the residues produced by the forest industry, Figure 8 shows the potential production of forest residues in CA.

[Figure 8 about here.]

It is estimated that the amount of logging residues produced in CA was around 26.8 million m³ (65 PJ), while the residues resulting from industrial processing were about 1.6 million m³ (4 PJ). However, due to the fact that these residues cannot be recovered to 100%, based on assumptions made in *section 2.1*, the amount of logging and wood processing residues that can be realistically harvested and collected is about 6.7 and 1.2 million m³, respectively (Figure 8). These quantities are equivalent to 16 and 3 PJ, respectively. Based on these results, it is estimated that a total of 7.9 million m³ (19 PJ) of forest residues could be available for bioenergy production in CA.

4.3. Agricultural origin

This term refers to all organic materials which are generated from harvesting of crops (also dedicated energy crops).

[Figure 9 about here.]

Major crops produced in the region are sugarcane, bananas, oil palm, maize, pineapples, rice, coffee, cassava, beans and plantains (Figure 9). Generally in CA, producers are more focused to commercialize the crop itself than producing energy from residues. Considering the rates at which agricultural residues are produced and the significant amount of land area dedicated to agriculture in CA, these constitute a significant potential biomass feedstock for energy conversion.

4.3.1. Agricultural residues

As with forest residues not all of the agricultural residues can be fully recovered due to that part of these must be left in situ to avoid soil degradation (i.e., reduction of the carbon stock in the soil), while other residues have competing uses such as fertilizer, fodder purposes, animal breeding and domestic fuel. For example, straw can be used as surface mulch for the control of soil erosion, food for livestock and domestic fuel (Ullah et al., 2015). The main benefit of producing energy carriers from agricultural residues is that these do not threaten food security, as may be the case when biofuels are directly produced from crops (first generation).

[Table 3 about here.]

The results presented in Table 3 show that the total amount of agricultural residues available in CA in 2011 was about 13 million tonnes (192 PJ). The countries with the highest potentials are Guatemala (79 PJ), Honduras (29 PJ) and Costa Rica (22 PJ).

The yield of agricultural residues depends on local conditions (soil type, soil fertility, weather, market, etc.) and thus can vary between different countries. Therefore, the top 6 residues generated in each country have been highlighted in Table 3. Regionally, the main residues coming from the agricultural sector are oil palm, maize, sugarcane, bananas and cassava. In 2011, about 4.9 million tonnes of maize residue and 2.9 million tonnes of banana residue were produced in CA.

Nowadays, the only agricultural residue used in the region to produce energy carriers at large scale is sugarcane bagasse. Currently, around 42% (21/50) of the sugar mills in the region produce CHP from sugarcane bagasse and supplied around 3% of the regional electricity demand in year 2011 (CEPAL, 2014). In Guatemala and Honduras about 67% and 100% of the sugar mills are already operating under CHP schemes firing bagasse, respectively. With respect to scale, one of the largest sugar mills in CA is San Antonio sugar mill (NSEL) located in Nicaragua, which is the top electricity producer in the region. In 2010, NSEL generated around 196 GWh (UN, 2011).

Other biomass used for CHP production in CA is coffee residue, although this is only used to fulfill in-house demand. As can be seen in Table 3, CA also has the potential to build a strong biofuel industry taking into account the production rates of oil palm, maize and sugarcane. Currently, the region has 23 plants producing biofuels (ethanol and biodiesel) using mainly sugarcane molasses (by-product of the sugar crystallization process) and African palm. Despite of this, there is not yet a biofuel market in the region that supplies the transportation sector. The potential biofuel production from agricultural crops in CA is out of the scope of this work as the main energy carriers under study are heat and power.

Agricultural residues (e.g., from pineapple and banana plantations) can also be used to produce biogas through anaerobic processes. An example of this is the pilot-scale biodigester located in Fabio Baudrit Agricultural Experiment Station of the University of Costa Rica. This plant is able to produce 5 256 GWh year⁻¹ (≈ 600 MW year⁻¹) from crop residues, animal manure and food wastes (ECPA, 2014).

Besides the results presented in this section regarding the significant

amounts of agricultural residues produced in CA. According to [Fischer and Shah \(2010\)](#), around 8% of CA's land area (3986 kha) has potential for sustainable expansion of cultivated area (wheat, maize, soybean, sugarcane and palm oil) and this share of land is within six hours travel time to a market. This is a key factor when designing systems based on agricultural residues as due to their low density, transporting large volumes of biomass to the processing plant is required to achieve attractive profit margins.

4.3.2. *Energy crops*

An energy crop is a plant especially grown to produce biofuels or when combusted/gasified to produce heat/power. Usually, these are short rotation crops with high yields requiring low inputs (e.g., fertilizer and water). Of special importance for the region are the short rotation coppices (SRC) or short rotation plantations of fast growing trees ([Cutz et al., 2013](#)).

In the region, several studies have been carried out to evaluate the use of short rotation crops for the production of energy carriers. For example, [van den Broek et al. \(2000\)](#) evaluated the use of eucalyptus to power a sugar mill, proposing the use of this crop to extend the cogeneration period of the sugar mill once the sugarcane season is over. However, it is worth mentioning that the drawback of using trees is their long growing cycle and low yields ($22 \text{ t ha}^{-1} \text{ y}^{-1}$ ([Alexopoulou et al., 2010](#))) compared to sugar crops ($122 \text{ t ha}^{-1} \text{ y}^{-1}$ ([Alexopoulou et al., 2010](#))) and some lignocellulosic crops such as the giant reed ($30 \text{ t ha}^{-1} \text{ y}^{-1}$ ([Alexopoulou et al., 2010](#))). [Cutz and Santana \(2014\)](#) evaluated the use of sweet sorghum (sugar crop) in CA to produce ethanol and CHP in a sugar mill, highlighting that the main advantage of using sweet sorghum is the short growing cycle (3 months) which would allow the sugar mills to process this crop during off-season and that the same harvesting and processing equipment could be used to process this crop.

With respect to the land area suitable for growing energy crops, here it is proposed that these must only be grown in land which cannot be used for food production or double-cropped with arable crops. Although it is known that crops grown on so-called marginal¹ land tend to report lower yields, current research shows that embracing these schemes might provide good results ([López-Bellido et al., 2014](#)) such as the use of cynara cardunculus, sweet sorghum or willow for the production of energy carriers.

It is important to mention that this paper does not suggest that the

¹Semi-arid areas characterized for having low quality soil with low water requirements.

use of energy crops will solve the energy needs of the region but they will clearly provide a significant potential to reduce the use of fossil fuels. Careful planning must be done with respect to the introduction of energy crop systems, especially when the use of new land might be under consideration or displacement of agricultural production is involved (i.e., direct and indirect land use change effects must be considered). In the case of developing countries such as CA, also other factors must be taken into consideration, e.g., land rights inequalities and weak institutions in charge of regulating and monitoring land use and land transactions. Standards and certification of energy systems must be a priority for policymakers in order to achieve a sustainable intensification of the agricultural systems. Key actions also involve providing technical support to farmers as there are many types of energy crops to choose from, each one with their corresponding physical constraints and land management requirements. The latter is a relevant issue as some energy crops might require intensive production schemes (especially for large scale systems), demanding large amounts of water and agricultural products which eventually will cause soil depletion and land degradation, as well as affecting other related systems (e.g., forage, biodiversity and cultural values). Thereby, all these indirect effects will result in that it is not obvious how to achieve a sustainable system for production of energy carriers from energy crops.

Besides reducing dependency on fossil fuel imports, the aim of introducing different energy crops in CA (obviously fitting the local growing conditions) is diversification of agriculture, which represents diversification of income as new farmers could serve the biomass market. Establishing new biomass markets will not only promote the creation of local jobs (from growing crops to the production of energy carriers) but may also provide other eco-systems services.

5. Technologies

This section discusses the general features of the different thermochemical technologies (combustion, gasification and pyrolysis) considered for the technology assessment in terms of scale, commercial status, complexity, efficiency and products. Through these conversion routes biomass can be transformed into energy carriers such as power, heat and transport fuel. The focus is on small and medium sized plants, i.e., combustion plants 1-150 MW_{th-input}, gasification plants 1.2-6 MW_{th-input} and pyrolysis plants 0.5-6 MW_{th-input}.

5.1. Combustion

Combustion of biomass is the least complex conversion route to transform biomass into refined energy carriers. Here, combustion refers to burning biomass in presence of air. Combustion systems are available from ICSs, small scale domestic boilers to large power boilers of several hundreds of MW_{th} . The combustion process produces flue gases at a temperature of around 800-1000 °C (McKendry, 2002a) and the thermal energy contained in the hot gases can be transformed into electricity (steam turbines and generator) and/or heat and process steam. The cost of electricity produced in biomass combustion plants varies from 3.9-12.4 ¢US/kWh (Evans et al., 2010), depending on the size of the unit.

One of the main advantages of biomass combustion over the other two thermochemical processes is versatility, allowing a wide range of feedstock from low to high moisture contents such as bagasse, logging and processing forest residues, agricultural residues (e.g., straw) and energy crops (Evans et al., 2010).

The scale of biomass combustion plants found in literature ranges from 6 to 520 MW_e Koornneef et al. (2007): with the smaller sizes typically applied in biomass and waste fired CHP schemes and the larger ones used for power boilers (electricity the main product) burning coal as fuel. Figure 10 presents efficiency of energy conversion from biomass to electricity for different combustion schemes, that is, fluidized bed/steam turbine (FB/ST), grate firing/steam turbine (GF/ST), bubbling fluidized bed/steam turbine (BFB/ST) and circulating fluidized bed/steam turbine (CFB/ST).

[Figure 10 about here.]

The most utilized combustors for CHP applications are fluidized bed boilers, either bubbling fluidized bed (BFB) or circulating fluidized bed (CFB) units. A main advantage of the fluidized-bed technology is its fuel flexibility, allowing combustion of fuels with different moisture (up to 60%), volatile and ash contents (<50%) (Bhaskar et al., 2011). Further, compared to grate fired boilers, the FB technology requires some more fuel preparation (smaller fuel particles). Fluidized-bed boilers applied for biomass combustion (CHP plants) have typically an electrical efficiency between 25 and 39% (Figure 10), typically limited by the alkali content of the fuel which causes high temperature corrosion if applying to high steam data (temperature).

As can be seen from Figure 10, among the fluidized-bed designs, the CFB/ST units stand out due to the high electrical efficiency (up to 39%)

and their scale, which is the dominant technology for large-scale applications. It is important to point out that this span in efficiencies aims to show the efficiency of different combustion technologies and does not infer that the CFB/ST is the best configuration as the selection of a combustion technology depends on several factors such as biomass properties, e.g., the alkali/metal content of the fuel and ash melting point. Furthermore, commercial systems can be found for both BFB and CFB design. [Koornneef et al. \(2007\)](#) analyzed the development and economic performance of fluidized bed combustion systems and they show that there are four major manufacturers that have built BFB installations with an installed capacity from 5 to 142 MW_e. Meanwhile, CFB units are provided by four major manufacturers ([Koornneef et al., 2007](#)) and these units have so far been built in the capacity range from 2 to 520 MW_e. With respect to the grate fired units, these are available in the range from 1 to 5.5 MW_e. A general problem in small scale units used for electricity generation is the low process efficiency, unless electricity generation is combined with the production of other energy carriers such as heat. Biomass units of smaller scale must be simple (low complexity), not requiring many operators and most likely involve generation of several energy carriers in order to get a reasonable total conversion efficiency.

With respect to smaller scale combustion systems (i.e., any biomass application limited to kW-size equipment for heating and cooking), this study considers that the introduction of improved combustion schemes such as ICSs is an urgent matter considering the current practice in CA (i.e., burning fuelwood in open fire stoves). Devices more sophisticated than ICSs are stoves burning processed fuels such as pellets. Yet, taking into account the cost of these systems (stove/fuel) and the current status of the biomass market in the region, there would be even higher barriers for deployment of these stoves than for ICSs. Other alternative technologies to ICSs are the so-called Advanced Cooking Stoves (ACSs), which include designs such as rocket stoves and gasifier stoves. The main difference between ICSs and ACSs is the better reduction of emissions/pollutants in the latter due to improved combustion efficiency ([Sambandam et al., 2015](#)). However, these units are still at an early stage of commercialization. More advanced small-scale technologies based on combustion are the thermoelectric units which comprise a boiler and a steam turbine for the production of CHP. These units are currently commercially available and their scales range from 1 to 100 kW_e and 100 to 300 kW_e, with a thermoelectric efficiency of 2-4% and 6-15%, respectively ([Coehlo et. al, 2015](#)).

Besides the problems of using biomass (e.g., fuelwood) in a non-sustainable

and inefficient way, problems related to indoor air pollution are of special importance. C. Barahona (2009) and Berrueta et al. (2008) have evaluated the implementation of ICSs with higher conversion efficiencies than open fire stoves in Honduras. They conclude that (commercially available) stoves can reduce fuelwood consumption in the range of 55-67%.

Table 4 shows the fuelwood saving potential if applying the findings by C. Barahona (2009); Berrueta et al. (2008) to CA, replacing traditional stoves for ICSs in all households using the year 2008 fuelwood consumption as reference.

[Table 4 about here.]

The introduction of ICSs in CA would result in an annual saving in the range of 4 - 8 Mt of fuelwood, which is equivalent to 59 - 113 PJ (Table 4). Besides reducing fuelwood consumption (deforestation), the implementation of ICSs will also lead to significant economic savings and improved health (less air pollution) for consumers. Table 5 presents the potential economic savings that could be obtained by using ICSs compared to open fire stoves.

[Table 5 about here.]

It is assumed that an open fire stove (reference case - the simplest stove) consumes $1.32 \text{ m}^3 \text{ month}^{-1}$ and a fuelwood price of $30 \text{ US\$ m}^{-3}$ (includes transportation costs, (Wang et al., 2013)). Based on these assumptions, it was estimated that the use of ICSs would yield savings to the fuelwood consumers in the range of 19 -152 US\$ year^{-1} .

5.2. Pyrolysis

Pyrolysis converts organics to solid (char), liquid (oil), and gas by heating in the absence of oxygen (Mohan et al., 2006). Typical temperatures range from 400 to 600 °C and can be carried out at atmospheric pressure, although higher pressures are preferred. Fast biomass pyrolysis is an interesting technology for the production of bio-oil, which can be further processed into transportation fuels (in conventional oil refineries) or used as feedstock in a gasifier (see section 5.3). The main drawback in the practical utilization of the bio-oil is its high oxygen content which should be reduced before processed in conventional refineries. The removal of the oxygen is done in a hydrotreating unit, where high pressure hydrogen is required. Hence, the upgrading of the bio-oil penalizes the energy efficiency of the whole process (Haro, 2013). The gas fraction is burnt to provide heat and power for the

pyrolysis. The char fraction has different uses: as a renewable fuel in conventional coal or domestic boilers, as a soil conditioner, for the manufacturing of activate carbon, or it can be mixed with the bio-oil fraction and fed to an entrained-flow (EF) gasifier. The main parameters in the modeling of (fast) pyrolysis products are in order of relevance: residence time, particle size, peak temperature, carrier gas, pressure, and biomass composition (Neves et al., 2011). Although the process is already in principle feasible it is still not commercial. The limitation for the commercialization of biomass pyrolysis is the high price of biomass as well as the cost of related systems. An example of promising projects is the Bioliq project in Karlsruhe (Germany) using straw and the IH² process developed by CRI Catalyst Company implemented in USA (Haro et al., 2014).

5.3. Gasification

Gasification refers to the partial combustion of biomass to produce a synthesis gas (syngas). The gasification process is carried out at temperatures in the range of 750-900 °C. The syngas produced from biomass mainly consist of H₂, CO, CO₂ and CH₄ with a LHV between 15 and 20 MJ kg⁻¹ (Bocci et al., 2014). The syngas composition mainly depends on the gasifying agent used in the process, i.e., air, steam or steam/CO₂.

Syngas can be used for direct firing in boilers or as fuel in the transportation sector, in stationary use such as in engines. The cost of electricity produced in biomass gasification plants varies from 4.2 to 9.6 ¢US\$ kWh⁻¹ (Evans et al., 2010), depending on the size of the unit.

The type of use of the syngas determines the requirements of upgrading and tar removal, with the highest requirements among the mature technologies when using the gas as fuel in gas engines (e.g., in small CHP plants). The syngas can also be further processed to obtain other fuels (e.g., ethanol and Fisher-Tropsch) and chemicals (e.g., methanol, acetic acid, olefins) (Haro et al., 2013). Currently, only the production of ethanol and methanol is done at commercial scale, e.g., the Enerkem Albert Biofuels plant located in Canada, which is able to produce 38 million liters of methanol and various chemicals from sorted municipal solid waste (Bacovsky et al., 2013). Meanwhile, the production of Dimethyl Ether and FT-liquids are still at pilot and demo scale. For example, the pilot plant at the Gas Technology Institute's (GTI) site located in the US which is able to process wood/algae to produce FT-liquids and gasoline-type fuel (Bacovsky et al., 2013).

There are two types of gasification processes: autothermal (direct) and allothermal (indirect), with the latter providing a less complex system. Indirect gasification can produce a nitrogen free syngas without an air separation

unit, while at the same time achieving a complete carbon conversion normally due to char that serve as fuel to produce heat for the gasification process such as in a twin-bed (combustion-gasification) system. With respect to reactors, these can be divided into fixed bed and fluidized bed. Fixed bed units are classified as updraft and downdraft, while among the fluidized bed designs both bubbling (BFBG) and circulating (CFBG) designs are used as gasifiers.

At present, there are 33 commercially operational biomass CHP facilities in the world (Task 33, 2014), where 31 of them are in Europe. The dominating system of the identified CHP plants is the downdraft gasifier connected to a gas engine. For example, the CHP plant located in Sulzbach-Laufen that uses a downdraft gasifier-gas engine scheme for the production of 130 kW_e and 280 kW_{th}. Other plants use an updraft gasifier connected to a Stirling engine. For example, the Flensburg CHP plant located in Germany uses an updraft gasifier with the syngas burnt in two Stirling engines for the production of 70 kW electricity and 280 kW heat.

Major drawbacks of the commercialization of gasification plants are the technical difficulties with respect to effective gas cleaning and the cost of the cleaning units which can be more expensive than the gasifier unit itself (Bocci et al., 2014). Reducing particulate matter, alkali metal species and tar content in the product gas is crucial and necessary for using syngas as fuel in a gas engine. When the power system is based on a boiler, syngas can be burnt directly without gas cleaning (providing an alkali content sufficiently low).

The efficiency (biomass to electricity) for different gasification schemes is presented in Figure 11, that is, FB gasification-atmospheric/combined cycle (FBG/CCa), FB gasification-pressurized/combined cycle (FBG/CCp), FB gasification-atmospheric/gas engine (FBG/GE), downdraft gasification/gas engine (DG/GE), BFBG/gas engine (BFBG/GE), CFBG/gas engine (CFBG/GE) and CFBG/steam turbine (CFBG/ST). It is important to point out that although Figure 11 only focuses on the gasifier efficiency, other parameters such as complexity, maturity of the technology and technology to remove tars/upgrading of the gas are crucial when assessing the overall performance and availability of the technology. Furthermore, fuel requirement is an important factor when selecting the type of gasifier to be used especially if residues are used for gasification. Variables such as water content, carbon content, alkali content, melting point of ash, shape and size of the biomass are all factors that determine if there will be operational problems such as clogging, fluidization and low quality of the syngas.

[Figure 11 about here.]

Trends for DG/GE, BFBG/GE, CFBG/GE and CFBG/ST are based on commercial systems on operation. The most utilized reactors for CHP applications are the DGs, where scale of available plants varies from 1.2-6 $\text{MW}_{th-input}$ and electrical efficiency ranges between 25% and 34%, respectively. With respect to medium-large scale CHP, CFB/ST systems are the most commonly used, where the scale of the plants on operation varies from 160 to 273 $\text{MW}_{th-input}$ and electrical efficiency ranges between 31 and 43%, respectively.

Based on data shown in Figure 11 which depicts the current status of gasification, it is concluded that the best-suited units to promote gasification in CA are the DG/GE systems, especially for small-scale production (1.2-6 $\text{MW}_{th-input}$). Main benefits of DGs over FB gasifiers are higher carbon conversion and thermal efficiency (Belgiorno et al., 2003). DGs also have the capability of processing a wide spectrum of biomass, e.g., wood chips, rice hull, cardboard and manure. The findings made by Roy et al. (2013) evaluating the performance of different feedstock (rice straw, eucalyptus wood, bamboo wood, coconut shell, among others) processed in a DG/ICE plant, indicate that a syngas with a heating value in the range of 4172 - 6967 kJ m^{-3} can be produced with a conversion efficiency between 77 and 86%. With respect to gas cleaning, DGs produce less particulate and tar ($< 10 \text{ g Nm}^{-3}$ (Bocci et al., 2014)) than other gasifiers (Belgiorno et al., 2003; Milne et al., 1999), which allows burning syngas in ICEs without a complex pre-treatment of the fuel gas. Furthermore, some gasifiers ($< 2 \text{ MW}_{th}$) equipped with a so-called “throat” are able to burn syngas in gas engines without further tar removal (van der Drift et al., 2008). At the same time, the advantage of using ICEs over other equipment (e.g., gas turbines) is that these have a higher tolerance to contaminants (Bridgwater, 1994). The allowed particulate and tar content for ICEs operation is up to as much as 50 g Nm^{-3} and 100 g Nm^{-3} , respectively. Furthermore, for small scales, DGs have one of the lowest specific investment costs compared to other small-scale systems. For example, the cost of a small-scale coal-fired power plant is 2535 € kW_{th}^{-1} (Wu et al., 2002), while cost for DGs vary between 829 € kW_{th}^{-1} and 1381 € kW_{th}^{-1} , depending on scale (Dornburg and Faaij, 2001).

6. Technology Assessment

The technology assessment presented in this section is based on a MCDM analysis described in section 2.2 and has the aim to support policymakers,

investors and stakeholders in the decision on which technology should be prioritized regarding biomass projects based within the CA region.

The linguistic assessment performed by the three decision-making groups for the four thermochemical technologies (BC, BG, BP and ICSs) discussed in the previous sections is presented in Table 6. The methodology used to transform the linguistic assessments into fuzzy numbers can be seen in *section 2.2*.

[Table 6 about here.]

From Table 6, it can be seen that according to the decision makers, key aspects to take into account when designing an energy system are resource availability, personnel competence, manufacturing equipment, engineering companies and incentives/subsidies. It is noteworthy that process efficiency is not ranked so high by decision makers as efficiency is more dependent on the state of technology of the unit (e.g., combustor, gasifier) than in factors such as the reuse of waste streams and improvement of process control, among others.

Table 7 presents the weighted ranking matrix for the four technologies analyzed.

[Table 7 about here.]

As was mentioned in *section 2.2*, the final ranking matrix, which represents the sequence of the four technologies can be determined by the fuzzy linear 0-1 programming (equation 10). Table 8 presents the final ranking matrix for the four technologies analyzed, where the most preferred technology is positioned in column 1 and the least preferred in column 4, that is, ICSs (1st), BC (2nd), BG (3rd) and BP (4th).

[Table 8 about here.]

As can be seen from Table 7 and Table 8, under the current conditions in CA, ICSs (0.53) are more suited to transform the biomass available than other competing technologies already available in the region (BC,0.41).

Figure 12 depicts the sequence (from the most preferred to the least) of the four technologies analyzed based on the technology assessment presented above.

[Figure 12 about here.]

Taking into account all 22 criteria defined in Figure 1, ICSs are the most preferred technology based on the survey of decision makers for near-time implementation in CA. In short-term, the region has still a number of challenges to overcome before advanced thermochemical processes such as gasification can be a realistic alternative. First, the region should place emphasis on the sustainable management of forests as well as improving its energy policy, strengthening relevant institutions, developing economic support schemes, and improving its business infrastructure. Thus, it is not the technology itself that hinders transformation of the current energy mix since there are already commercial technologies available (including large scale systems, see *section 5.3*), instead the challenge is in taking these technologies to the rural areas where most biomass is consumed and establish the necessary infrastructure to support the entire biomass value chain. For this reason, this analysis considers that if CA had to choose an immediate path to improve the use of biomass, ICSs should be the preferred technology considering its low complexity compared to the other studied technologies, while at the same significant reductions in indoor pollution (compared to open fires) can be achieved. Further, ICSs can help establishing a sustainable biomass supply infrastructure which, in turn, later can be used as a base to establish more advanced biomass conversion systems. However, one of the main problems in implementing ICSs is the high upfront investment cost for the households. Typical cost for ICSs ranges from 60 to 150 US\$ (Wang et al., 2013), which is too expensive to afford for low-income households. In fact, a large portion of the households in CA have a low income and they are the ones usually using fuelwood to meet their basic needs; according to statistics from the World Bank Database (2014), in Year 2009, around 16.9%, 29.8% and 14.6% of the population in El Salvador, Honduras and Panama, respectively, were living with less than US\$2 a day. Corresponding figures for Costa Rica, Guatemala and Nicaragua are not available.

Other barriers related to the deployment of ICSs is the low price of a traditional stove, which ranges from 3 US\$ to 10 US\$ (World Bank, 2013). Yet, as shown in Table 5 (*section 5.1*), including the investment cost, ICSs still yield higher savings to fuelwood consumers compared to traditional stoves if applying an interest rate of 25%. The total savings during the first year of implementation would be in the range of 19-152 US\$. Thus, if at all realize some of the potential from implementing ICSs, it is of importance that there will be some governmental low-interest rate loans for consumers to stimulate investments in ICSs due to it is well known that private consumers in reality apply very high interest rates (Newlon and Weitzel, 1991). Further, to give an example of the discount rate implicit in the choice that consumers

make between open fire stoves and ICSs in CA, it is assumed an average purchase price for open fire stoves of 6.5 US\$ with an annual operating cost (fuelwood cost) of 479 US\$. Meanwhile, for ICSs it is assumed an average purchase price of 108 US\$ and an annual operating cost (fuelwood cost) of 223 US\$.

The implicit discount rate (r) is estimated based on the following equation (Newlon and Weitzel, 1991):

$$\frac{S}{1+r} + \frac{S}{(1+r)^2} + \frac{S}{(1+r)^n} = I \quad (12)$$

Where S represents the annual savings due to the investment on an efficient technology, I the investment required to achieve the savings and N , the numbers of years over which the savings are realized.

Based on the aforementioned assumptions, it was estimated that the 101 US\$ additional investment required to achieve the savings provided by the ICSs produces an extremely high rate of return, over 250% if it last 10 years. This is another factor that could be used to explain why ICSs in CA have been adopted very slowly, indicating that consumers rather spend their money on something that can give more immediate feedback than on improved energy efficiency measures. Other challenges that further limit the dissemination of ICSs are changes in cooking practices, versatility of open fires (e.g., open fire stoves are also used for drying clothes and keep away insects), lack of financial incentives and minimum quality standards (e.g., durability) for manufacturing ICSs (Wang et al., 2013). The access to reliable information (Newlon and Weitzel, 1991) is also a critical aspect for the deployment of energy efficient technologies such as ICSs. This is because, in order to make consumers to buy a more efficient unit, it is important to make sure that they are capable of accessing and understating the available information regarding the technology in order to evaluate the trade-off between the current cost and the future benefits of achieving energy efficiency (Newlon and Weitzel, 1991).

With respect to biomass combustion, placed at 2nd position, nowadays in CA, this is the only technology used in large-scale biomass applications. As mentioned above, the biggest CHP producers firing biomass as raw material are sugar mills, which burn sugarcane bagasse resulting from the milling process. These CHP plants are based on grate fired low-pressure boilers (dominating technology) and back-pressure steam turbines (BPST) with an overall process efficiency of 20% (Carneiro de Miranda and Van den Broek, 1998). In recent years, CA sugar mills have been implementing more advance co-generation schemes with higher steam data and condensing-extraction steam

turbines (CEST) that enable them to reach overall efficiencies (electricity + process steam) around 55% (Larson et al., 2001). These systems allow sugar mills not only to fulfill internal process heat demand but also sell the electricity surplus to the national grid. However, the main problem of burning sugarcane bagasse to produce heat and power in CA is climate conditions. During the rainy season, sugarcane transport from the fields to the processing plant becomes very difficult, which is one of the reasons behind the short operation period of sugar mills (around 100 days (Cutz et al., 2013)). Therefore, the challenge for industries that already have equipment capable of processing biomass relies on implementing new systems that reduce the complexity of transporting biomass during rainy season or integrating other feedstocks into the processing chain (e.g., eucalyptus and sweet sorghum). These measures are intended to allow processing plants to extend the production cycle of CHP or reduce the fossil fuel consumption during off-season. In this context, a successful example of extending the operation period by using other biomass fuels is seen in Nicaragua, where the San Antonio sugar mill uses eucalyptus to produce 17 MWh of electricity during off-season.

It is worth mentioning that recent studies propose the use of alternative technologies such as gasification and hydrolysis to maximize CHP and ethanol production from bagasse (Benjamin et al., 2013; Pellegrini and de Oliveira Jr., 2007). However, a study made by Dantas et al. (2013) comparing the productivities and costs of different technological routes to produce energy carriers from bagasse indicate that, even if alternative technologies such as bagasse gasification to produce CHP or bagasse hydrolysis to produce ethanol are deployed, burning bagasse is still by far the least cost option. The cost reduction necessary to make bagasse gasification and bagasse hydrolysis compared to conventional combustion of bagasse is 48% and 43%, respectively (Dantas et al., 2013).

With respect to biomass gasification, placed at 3rd position, according to the authors and information provided by Higman (2013), currently in CA, there are no operating gasification plants and there are no plans to build such type of plants in the coming years. Yet, there is one biomass power project near the region already using gasification technology. As part of the UNIDO/UNEP/GEF project, a 50 kW biomass fired demonstration gasifier was built in Cuba to study the techno-economic feasibility of gasification using local forest biomass (UNIDO, 2015). The plant produces electricity for 96 households, a bakery, a primary school and for the water supply system (UNIDO, 2015). This project could provide valuable experience (transfer of technologies for the design, start-up and operation) for future projects in the CA region.

Based on assumptions made in this work (*section 2.2*), Figure 13 presents the potential electricity production from potential recoverable forest residues for different combustion/gasification configurations.

[Figure 13 about here.]

As can be seen from Figure 13, by implementing gasification power plants based on DGs or FBGs running with logging residues, the region could reach scales between 96 and 175 MW_e. Meanwhile, if processing residues are destined for electricity production, the region could reach scales between 17 and 31 MW_e. On the other hand, with the use of competing technologies such as combustion plants, capacities up to some 150 MW_e could be reached (GF/ST and CFB/ST) when using forest residues as a fuel. The decision between selecting a combustion or gasification technology is obviously related to what energy carriers are of interest for the region. For example, direct combustion of biomass release energy that can be used to produce steam which later on can be used to power a steam turbine to generate electricity. Gasification of biomass produces a lower heating value gas, which can be used to power gas engines/gas turbines. The waste streams of the gasification process could also be used to produce process steam. Furthermore, as mentioned in *section 5.3*, syngas can also be upgraded to obtain other fuels such as ethanol or chemicals. Thus, it can be expected that each subsequent process conducted to produce an additional by-product will increase the overall efficiency (McKendry, 2002b) and consequently improve the economics of the conversion process.

From this, it can be concluded that the use of biomass-based technologies capable of producing more than one energy carrier will be crucial for CA in the next coming years. Especially, the deployment of small-scale commercial systems (when biomass is available within a 50 km radius (Wu et al., 2002)) for the production of power, which can help to tackle one of the main problems in rural areas, i.e., access to electricity. This proposal is also supported by the high price of electricity in some CA countries (MIF/BNEF, 2013), which opens the possibility for using local biomass to produce energy carriers.

The creation of small community-based organizations such as cooperatives to run small-scale electricity plants can be a good alternative to implement and gain experiences from these technologies. Yet, the technologies chosen should have a low complexity and be able to handle variations in quality and flow of the fuel. A cooperative effort could also reduce the cost of collection, handling, transport and maintenance activities. Obviously, the success of these projects will depend on the capacity building of

households, communities and institutions (non-governmental as well as governmental). Successful stories are already found in the region with respect to rural communities working in cooperatives towards a common goal. For example, rural communities all over CA, especially in Guatemala, Nicaragua and Costa Rica work cooperatives plan to grow, harvest and sell products such as coffee, honey and vegetables ([Root Capital, 2015](#)). The cooperative scheme allows the members to access better market prices and facilitate the transfer of technology and techniques regarding the production process.

Although the electric efficiency would be clearly penalized at small-scale systems, having the possibility to rely on “low-cost” energy carriers from local resources is a good opportunity for households to reduce health issues related to the cooking and heating methods (open fire stoves), and improve their quality of life in a broader sense. Rural households can benefit from accessing off-grid electrification systems by using electricity to power machinery for manufacturing goods (labor-saving appliances) that will provide income. These cash earnings will not only help households to pay for the electricity consumed during the production process but also for the energy bill. In this context, a study made by [Grogan and Sadanand \(2013\)](#) analyzing the effects of rural electrification in Nicaragua showed that household electrification is associated with reducing household work for women under 35 years of age, which are 23% more likely to work outside the home after electrification, thus increasing family earnings.

With respect to biomass pyrolysis, no discussion has been provided here, as pyrolysis is concluded to be the least preferable technology for the CA region. Also, according to the authors knowledge there are currently no plans to build any BP plants in CA.

In summary, it is conclude that factors such as the lack of engineering companies ([MIF/BNEF, 2013](#)), manufacturing equipment ([MIF/BNEF, 2013](#)), incentives/subsidies, and the low state of technology in the region have strongly limited CA’s capacity to move away from the first step of the technology ladder shown in Figure 12. Another key factors that have held back the deployment of efficient technologies are the low level of educated personnel and rate of project development. For example, currently, most of the pilot, semi-commercial, commercial gasification projects are being realized within the European Union, where each of these plants are the results of alliances between firms and academic units ([Hellsmark and Jacobsson, 2012](#)). This clearly evidences a high knowledge transfer between the companies and the academy, which consequently have helped to improve personnel competence and gain technical experience regarding new technologies, whereas in CA these kinds of synergies are not yet established. Thus,

it should be important to find ways to improve the personnel competence in CA, and as part of this, to develop links between different institutions involved in the development and commercialization of biomass processes.

Finally, in addition to the conclusions that can be drawn from the present study, we conclude that it is critical for the CA region to also improve local policies and regulation with respect to:

- Reduction of the cost of green microloans. Average cost of microloans² in CA is 15.6% (MIF/BNEF, 2013), while in Brazil and Argentina the cost of green microloans is 2.5% and 3% respectively (MIF/BNEF, 2013).
- Creation of policies aimed at offsetting GHG emissions. This include the creation of incentives (infrastructure fund, tax relief, import duty) as well as market instruments to reduce the carbon footprint.

The improvement of existing energy policies or the creation of new efficient ones will attract local and international capital to increase the penetration and investment in bioenergy projects.

7. Conclusions

A review and an assessment of conditions for increased and efficient use of biomass in Central America (CA) is given. Then, a Fuzzy Multi-Actor Multi-Criteria Decision-Making (MCDM) method is applied to identify a portfolio of biomass conversion technologies appropriate for CA, considering technical, economic, environmental and socio-political aspects. The study is motivated by the fact that the economic growth and industrialization of CA, as well as the low electrification rates in some of the countries in CA is likely to lead to an increase of energy consumption in the next coming years and, thus, it should be important that as much as possible of such transformation of the energy system can be made in a sustainable way using the potential for renewable energy supply. The review of biomass supply shows that although CA has relatively limited resources of fossil fuels, the region has a significant potential of lignocellulosic biomass resources, which indicate that biomass could become the flagship clean energy source in the future energy mix.

Based on the Fuzzy Multi-Actor Multi-Criteria Decision-Making methodology, which included 22 different conflicting criteria, 3 decision-making groups evaluated the performance of four different biomass-based technologies, i.e., improved cooking stoves, combustion, gasification and pyrolysis.

²data for Belize and Salvador was not available.

According to the decision-makers, crucial aspects to take into account when designing an energy system are (in order of importance) the following: resource/availability, personnel competence, engineering companies, market availability, incentives/subsidies and manufacturing equipment. All aforementioned factors are key parts of a biomass value chain and critical for the economics and success of biomass projects. Other factors that do not depend on local conditions but are still important to consider based on the MCDM analysis are state of technology, complexity, market stability, manufacturer's warranty and process efficiency.

Results from the MCDM analysis show that the most suitable technologies to be firstly implemented in the region are improved cooking stoves and combustion. The main benefit of implementing ICSs in short-term is that this technology would help to tackle one of the biggest problems in CA, which is indoor pollution. With respect to advanced schemes, the region can take advantage of larger economies of scale that already have a well-developed technology to produce green energy carriers.

Finally, it is important to mention that the benefits from improving energy efficiency, reducing unsustainable biomass use and improving public health clearly outweigh the societal cost of biomass technologies but obviously require firm policy in order to take place. Policies that promote the use of local resources, deployment of biomass technologies and the creation of a well-defined biomass market as well as supporting research on biomass conversion processes are critical. Social-marketing awareness campaigns should also be strongly taken into account, as they are crucial to project success, especially in rural communities where, for example, it has been seen that the current high price of the ICSs has slowed down the adoption of efficient technologies.

Notation

*ACS*s= advanced cooking stoves;
BC= biomass combustion;
BFBG= bubbling fluidized bed gasifier;
BG= biomass gasification;
BP= biomass pyrolysis;
BPST= back-pressure steam turbines;
CA= Central America;
CC= combined cycle;
CEST= condensing-extraction steam turbine;
CFB= circulating fluidized bed;

CFBG= circulating fluidized bed gasifier;
CHP= combined heat and power;
CM= cattle manure;
DG= downdraft gasifier;
FB= fluidized bed;
FBG= fluidized bed gasifier;
FW= fuelwood;
GE= gas engine;
GF= grate fire;
GHG= greenhouse gas emissions;
ha= hectare;
ICE= internal combustion engine;
ICs= improved cooking stoves;
IR= industrial roundwood;
LHV= lower heating value;
MCDM= Fuzzy Multi-Actor Multi-Criteria Decision Making;
Mtoe= million tonnes of oil equivalent;
Mbbl= one thousand barrels;
PM= swine manure;
RES= renewable energy resources;
RPR= residue product ratio;
ST= steam turbine;
TS= total solids;
w.b.= wet basis;
VS= volatile solids;

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(a)

(b)

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Table 1: Residue product ratio (RPR) and LHV for different agricultural values.

	Type of residue	RPR	Ref.	LHV (MJ kg ⁻¹)	Ref.	Type of residue	RPR	Ref.	LHV (MJ kg ⁻¹)	Ref.
Bananas	Stalks and peels	2	[a]	13.1	[b]	Pigeon peas				
Beans	Trash	1.4	[a]	12.8	[a]	Plantains	Stalks and peels	1.4	[a]	12.8
Cashew nuts	Trash and shells	2.1	[c]	14.2	[d]	Rice	Straw	2	[a]	13.1
Cassava	Stems and peels	0.4	[a]	13.1	[a]		Husks	0.45	[f]	8.83
Cocoa	Pods, husk	1	[c]	18	[e]	Roots and tubers		0.23	[f]	12.9
Coconut	Husk	0.42	[e]	19	[e]	Stalk		0.5	[c]	17.5
	Shells	0.7	[e]	18	[e]	Stalk		3.5	[c]	15.9
Coffee	Husks	1	[a]	15.4	[a]	Seed cotton	Trash	2	[c]	15.5
Groundnuts	Trash and shells	2.1	[a]	11.2	[f]	Sesame seed		2.62	[c]	17.8
Maize	Stalk	2	[g]	16.3	[g]	Sorghum	Stalk	2.5	[c]	18
	Cobs	8.7	[g]	12.6	[g]	Soybeans	Stalk, leaves, shell	0.3	[g]	15.8
Oil, palm fruit	Empty fruit bunches	0.25	[c]	15.51	[c]	Sugar cane	Top & trash	0.4	[a]	16
Pineapples		1	[c]	14	[e]	Sweet potatoes	Vines and peels	1.2	[c]	15.6
						Wheat	Straw			

[a] Amoo-Gottfried and Hall (1999), [b] Tock et al. (2010), [c] Eisentraut (2010), [d] ?, [e] Milbrandt (2009), [f] Sajjakulmukit et al. (2005), [g] Perera et al. (2005), [h] Jingura and Matengaifa (2008), [i] Jiao et al. (1999), [j] Maas et al. (2008).

Table 2: Linguistic variables for ranking criteria and alternatives.

Importance		Performace		Scale
Lowest	LT	Worst	WT	(0.0,0.0,0.1)
Lower	LR	Worse	WE	(0.0,0.1,0.3)
Low	L	Bad	B	(0.1,0.3,0.5)
Medium	M	Medium	M	(0.3,0.5,0.7)
High	H	Good	G	(0.5,0.7,0.9)
Higher	HR	Better	BR	(0.7,0.9,1.0)
Highest	HT	Best	BT	(0.9,1.0,1.0)

Table 3: Production and residue of different agricultural crops in Central America.

	Bananas	Beans	Cassava	Coconuts	Coffee	Maize	Oil, palm fruit	Pineapples	Plantains	Rice	Sorghum	Sugar cane	Total
Belize													
ACP (t)	74 117	3704.0	337.0	735.0	45.0	62 705		1114.0	11 000	19 081	11 617	844 000	
QR (kt)	37	1	0.0	0.1	0.0	84	0.0	0.1	6	2	8	63	200
EP (TJ kg ⁻¹)	485	17	0.4	2	0	1212	0	1	72	18	135	1000	2943
Costa Rica													
ACP (t)	1 937 122	15 713	516 636	8000	100 083	18 501	1 050 000	2 268 956	90 000	278 975		3 418 193	
QR (kt)	969	5	52	1	25	25	66	142	45	24	0	256	1609
EP (TJ kg ⁻¹)	12 688	70	677	21	385	658	1018	1985	590	484	0	4051	22 626
El Salvador													
ACP (t)	38 442	64 835	28 867	60 300	82 095	756 352	5784	11 673	11 673	25 589	141 997	9 898 968	
QR (kt)	19	23	3	8	21	1012	0.0	0.4	6	2	93	742	1929
EP (TJ kg ⁻¹)	252	290	38	156	316	14 618	0	5	76	24	1656	11 730	29 161
Guatemala													
ACP (t)	2 679 934	199 912	18 492	22 785	242 839	1 672 241	1 653 000	234 520	188 722	30 381	47 181	20 586 052	
QR (kt)	1340	70	2	3	61	2237	103	15	94	3	31	1544	5502
EP (TJ kg ⁻¹)	17 554	896	24	59	935	32 319	1602	205	1236	28	550	24 394	79 803
Honduras													
ACP (t)	755 365	91 149	23 591	14 800	282 361	583 020	1 556 348	138 280	84 159	48 902	37 000	7 671 000	
QR (kt)	378	32	2	2	71	780	97	9	42	4	24	575	2016
EP (TJ kg ⁻¹)	4948	408	31	38	1087	11 268	1509	121	551	45	431	9090	29 528
Nicaragua													
ACP (t)	39 645	234 163	75 085	6202	103 664	523 000	86 700	56 815	64 463	488 000	91 029	5 937 500	
QR (kt)	20	82	8	1	26	700	5	4	32	41	60	445	1423
EP (TJ kg ⁻¹)	260	1049	98	16	399	10 108	84	50	422	451	1061	7036	21 034
Panama													
ACP (t)	328 377	2835	21 186	14 354	13 079	77 306	55 200	83 218	74 280	269 861	3628	2 263 889	
QR (kt)	164	1	2	2	3	103	3	5	37	23	2	170	517
EP (TJ kg ⁻¹)	2151	13	28	37	50	1494	54	73	487	249	42	2683	7360

ACP stands for crop production, QR refers to the quantity of residue produced and EP stands for energy potential. Values for ACP were extracted from [FAO \(2014\)](#), year 2011.

Table 4: Fuelwood saving potential in CA if ICSs are introduced in all households.

	Consumption Mt	Saving Potential					
		Mt			PJ		
		Onil	Justa	Patsari	Onil	Justa	Patsari
Belize	0.20	0.07	0.11	0.14	0.96	1.52	1.85
Costa Rica	1.02	0.36	0.56	0.68	4.86	7.64	9.31
El Salvador	1.27	0.44	0.70	0.85	6.03	9.48	11.55
Guatemala	5.20	1.82	2.86	3.48	24.78	38.94	47.43
Honduras	2.58	0.90	1.42	1.73	12.33	19.37	23.60
Nicaragua	1.81	0.63	1.00	1.21	8.63	13.56	16.52
Panama	0.35	0.12	0.19	0.23	1.66	2.60	3.17
Total	12.42	4.35	6.83	8.32	59.25	93.11	113.42

Fuelwood consumption data was extracted from [FAO \(2014\)](#). It was assumed that fuelwood has a density of 300 kg/m³ and a LHV of 13.63 MJ/kg ([Wood Energy, 2015](#)). The LHV was defined as the average between the LHV in dry matter and as received ([Wood Energy, 2015](#)).

Table 5: Economic saving potential if ICSs are introduced to all households in CA.

	Cons. of FW ^[a] m ³ yr ⁻¹	Cost of FW ^[a] US\$ yr ⁻¹	Savings (FW ^[a]) US\$ yr ⁻¹	Investment Cost US\$	Total expenses (1st yr) US\$ yr ⁻¹	Total savings (1st yr) US\$ yr ⁻¹
Open fire stove	16	479		8	487	
Onil	10	311	168	156	467	19
Justa	7	215	263	141	356	131
Patsari	5	158	321	88	245	241
Ecofogón	8	239	239	144	383	104
La Chapina	6	191	287	144	335	152

^[a] Fuelwood.

Table 6: Linguistic assessment by Group 1 - *Carlos III University of Madrid*, Group 2 - *AICIA* and Group 3 - *Chalmers University of Technology*.

No.	Criteria	Importance	Technology				ICSs
			Pyrolysis	Combustion	Gasification	Performance	
1	Moisture	M,L,M	WE,WT,B	M,B,G	B,WE,M	M,B,B	M,B,B
2	Ash/alkali content	M,L,R,H	B,WE,B	G,BT,B	B,B,M	G,BR,G	G,BR,G
3	Climate conditions	M,HR,HR	WE,WE,WE	WE,B,WE	WE,B,WE	B,WT,WE	B,WT,WE
4	Resource availability	HR,HT,HT	B,M,WE	B,G,WE	B,WT,WE	M,WE,WT	M,WE,WT
5	State of technology	H,HT,M	G,G,WE	BR,BT,G	G,B,WE	BT,BR,G	BT,BR,G
6	Scale of operation	M,HR,M	M,B,WT	BT,BR,G	M,M,WE	BT,G,M	BT,G,M
7	Complexity	HR,H,H	M,G,WE	BR,G,M	M,B,WE	BT,BT,BR	BT,BT,BR
8	Biomass pre-treatment	M,M,H	M,B,WE	G,BR,G	M,WT,M	BR,G,BR	BR,G,BR
9	Cleaning systems	M,HR,H	M,G,WT	M,BT,G	G,WT,WT	M,WT,BR	M,WT,BR
10	Residues (amount of non-ash residues)	H,L,H	B,B,WE	M,BT,G	M,G,M	M,G,G	M,G,G
11	Process efficiency	M,M,M	B,M,WE	B,B,G	G,G,M	B,WE,M	B,WE,M
12	Personnel competence	HT,H,H	WT,B,WT	G,BR,M	WT,WE,WT	BR,BR,G	BR,BR,G
13	Manufacturing equipment	HR,HR,HR	WE,M,WE	B,BT,B	WE,WT,WE	M,BR,G	M,BR,G
14	Engineering companies	HR,HT,HR	WE,B,WT	M,BR,WT	WE,WT,WT	G,G,M	G,G,M
15	Investment	H,HT,H	M,G,WE	G,BT,B	M,WE,WE	G,BT,BR	G,BT,BR
16	Polygeneration	M,M,M	M,M,M	M,WT,WE	G,BR,G	B,WT,WE	B,WT,WE
17	Versatility	M,H,H	M,G,M	M,BR,B	G,M,G	B,WT,B	B,WT,B
18	Market availability	HT,M,H	M,M,G	BR,B,G	B,G,B	BR,G,G	BR,G,G
19	Market stability	HT,M,H	WE,G,WE	M,G,WE	WE,B,WE	M,BT,G	M,BT,G
20	Environmental impact	H,H,HR	WE,B,WT	B,BT,G	M,BR,M	B,WT,G	B,WT,G
21	Manufacturer's warranty	HR,H,H	WE,B,WT	M,G,B	WE,WT,WE	B,BR,M	B,BR,M
22	Incentives and subsidies	HT,H,H	WT,G,G	G,WT,G	WT,G,G	B,BR,WE	B,BR,WE

Table 7: Ranking matrix of technology assessment.

	1	2	3	4
BP	0.00	0.13	0.51	0.35
BC	0.41	0.52	0.07	0.00
BG	0.15	0.10	0.17	0.58
ICSs	0.53	0.15	0.21	0.11

Table 8: Final ranking matrix of technology assessment.

	1	2	3	4
BP	0	0	1	0
BC	0	1	0	0
BG	0	0	0	1
ICSs	1	0	0	0