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Switching to efficient technologies in traditional biomass intensive countries: The resultant change in emissions

L. Cutz[a,*], O. Masera[b], D. Santana[a], A.P.C. Faaij[c]

[a] *Universidad Carlos III de Madrid, Av. Universidad 30 - 28911 Leganés, Madrid, Spain*
[b] *Institute for Ecosystems Research and Sustainability, National Autonomous University of Mexico, AP 27-3 Xangari 58089, Morelia, Michoacán, Mexico*
[c] *Center for Energy and Environmental Sciences, Faculty of Science and Engineering, University of Groningen, Nijenborgh 6, P.O. Box 221, 9700 AE Groningen, The Netherlands*

Abstract

This paper aims to quantify the benefits of switching from a system dependent on traditional biomass to systems running on more efficient fuels and technologies. It is estimated that even when open fires burning fuelwood are replaced by improved cooking stoves (ICSs) and liquefied petroleum gas (LPG) stoves, and biomass is processed in dedicated biomass power plants, a net reduction in CO_2 emissions is still obtained. The ICS/LPG stove/biomass combustion power plant configuration could provide an average net reduction of 84 kg-C_e/tDM. Meanwhile, a net reduction of 105 kg-C_e/tDM could be obtained when implementing a ICS/LPG stove/biomass gasification power plant scheme. Main factors influencing the net reduction of CO_2 emissions are technology efficiency and the fraction of non-renewable fuelwood use.

The switch from traditional biomass to modern biomass in traditional

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[*] Corresponding author. Tel: +34 916248371
Email address: `lcutz@ing.uc3m.es` (L. Cutz)

biomass intensive countries must not only be done to reduce CO_2 emissions but also to avoid indoor pollution and energy poverty. Health improvements should be more important than energy savings. Results also indicate that the use of modern biomass systems not only could provide a reduction of local environmental pollution, but also could boost the local economy by the creation of biomass infrastructures.

Keywords: Traditional biomass; Bioenergy; Developing countries; CO_2 emissions.

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1. Introduction

In the last few decades, fossil fuels have played a leading role in the global energy mix. The reason for this dependence could be explained by the still abundant fossil fuel resources and reserves (AGS, 2011), which has put on the soft pedal the exploitation of other energy resources. In average, during the period 2003-2013, around 87% (BP, 2014) of global primary energy was supplied by fossil fuels: coal, oil and natural gas. Despite the fact that renewable energy (RE) stills play a relatively minor role in global energy consumption, RE shows an upward trend increasing its participation from 0.7% in 2003 to 2.2% in 2013 - excluding hydro (BP, 2014). It is clearly seen that the quest for energy self-sufficiency, combined with the promotion of green energy policies (e.g., green targets introduced by the Kyoto Protocol), is motivating countries to increase the participation of renewable resources in their energy mix. While the production of modern energy carriers from renewable resources has taken place for several decades, in some parts of the world renewable resources such as biomass (e.g., fuelwood) are still used in its most basic form (from the conversion perspective) to meet energy needs such as domestic cooking and space heating. It is estimated that around 2.6 billion people worldwide (Masera et al., 2015), half the population in developing countries, burn solid biomass to meet their basic energy needs. Figure 1 presents world biomass consumption for ten years prior to 2010.

[Figure 1 about here.]

According to data released by World Bank (2016), the average traditional biomass usage for the period 2000-2010 was around 72% of global biomass consumption. Traditional biomass consumption "hotspots" are concentrated in Sub-Saharan Africa, Easter Asia, Southern Asia, South Eastern Asia and Latin America & the Caribbean. Although it is seen in Figure 1 that there has been an expansion of modern biomass, traditional biomass consumption in 2010 was 17% higher than the year 2000 and its consumption is expected to increase at least through 2030 (Masera et al., 2015). In some regions, biomass usage is expected to increase at the same rate as the population (Karekezi et al., 2004). Thus, it is clear that traditional biomass is a major global problem and disproportionately affects the world's low-income regions. The main problem of the use of traditional biomass is that when used as fuel, biomass is burnt in enclosed areas, directly exposing humans to emissions and particulates such as carbon monoxide (CO), benzene (C_6H_6) and other polycyclic aromatic hydrocarbons (PAHs), which are a threat to human health.

These compounds are usually found in house dust, which is a key route of exposure to contaminants either by ingestion or inhalation (Choi et al., 2010). Furthermore, studies indicate that traditional wood fuels, via unsustainable harvesting and burnt through low efficient technologies (incomplete combustion), contribute approximately to 2% of global greenhouse gases (GHG) emissions (Bailis et al., 2015). Obviously, depending on the degree of dependence that countries have on unsustainable biomass, this behavior leads to lower or higher levels of risk to the environment and human health. For instance, it is known that only in Central America (CA) around 37 thousand people (World Bank, 2013) die annually caused by indoor air pollution. It is also estimated that about 50% of the population in CA uses fuelwood in open fires to meet their basic energy needs (ECLAC, 2010) and around 7 million people (Dolezal et al., 2013) have limited or no access to electricity. Other impacts of the use of traditional biomass have been extensively investigated and discussed in a review paper by Masera et al. (2015). The review covers the available literature regarding the role of traditional biomass on deforestation and forest degradation, emissions from traditional biomass combustion and the barriers preventing the adoption of more sustainable technologies (e.g., stacking).

The aim of this paper is to estimate the CO_2 abatement potential by the implementation of schemes with high efficiency biomass technologies against the performance of open fires. In this study, four technologies were explored and evaluated across a series of "what-if" scenarios, (1) ICSs, (2) LPG stoves,

(3) biomass combustion power plants and (4) biomass gasification power plants. As the environmental performance of the scenarios considered here has a strong dependence on the conversion efficiency, the net reduction of CO_2 emissions is compared in terms of the electrical efficiency and overall efficiency of the power plants. So far, very few papers have quantified the benefits of different technologies and fuel combinations for catering to different energy needs in traditional biomass intensive systems. Of these studies, Johnson et al. (2009) estimate the carbon savings from improved biomass cookstove projects. This paper uses fuel consumption and emission estimates obtained from community-based sampling, combined with spatially explicit community-based estimates of the fraction of non-renewable fuelwood use (fNRB), to estimate the CO_2 savings from replacing open fires with improved Patsari stoves in a region of central Mexico. The results indicate that CO_{2e} savings ranged from 1.6 to 7.5 tCO_{2e}/home/yr for renewable and non-renewable biomass use in individual communities, respectively. Martínez-Negrete et al. (2013) analyzed if the modernization of a Mexican village made it more energy efficient and cleaner from an environmental perspective. The study reports a rise of CO_2 emissions, mainly due to an increase in the share of fossil fuels used for electricity generation and transportation. Unlike Johnson et al. (2009), the authors considered more advanced energy carriers such as LPG and electricity (fossil fuel power generation) but estimates of fNRB are not considered in the calculations. Martínez-Negrete et al. (2013) assume that all fuelwood consumption is renewable.

Our paper extends these previous contributions by adding more complex technologies than ICSs such as small-scale dedicated biomass power plants. The main new contribution of this work is that an integrated approach is used to examine the interplay between a wide portfolio of fuels and technologies, considering an energy penalty on the use of LPG and the fraction of non-renewable fuelwood use in the calculation of the CO_2 abatement potential. The use of the fNRB in the calculations is crucial as it prevents overestimating the CO_2 savings from displacing traditional biomass by avoiding the assumption that all biomass burnt in open-fires and ICSs is non-renewable. According to data reported by Masera et al. (2015), in 2014, on the 287 projects being implemented in 47 countries to generate carbon credits by reducing traditional biomass consumption, the median fNRB used to estimate the emission reductions was 89%. Nevertheless, a recent pantropical assessment on traditional biomass reports fNRB values 60-70% lower than the median value used in those 287 projects. It is estimated that the share of unsustainable biomass represented 27-34% (depending on the region) of the global fuelwood harvested in 2009 (Masera et al., 2015). Therefore, for the present calculation, we considered a fNRB value of 30% in accordance with Bailis et al. (2015). Further, in order to show the long-term environmental impact of implementing the systems proposed here, we estimate the potential net reduction in CO_{2e} emissions for 2050.

2. Materials and Methods

In this study, biomass is classified as either traditional or modern, based on the end-use of biomass and the conversion technology employed. Traditional biomass is used for cooking and space heating, usually burnt in open fires or three-stone cooking stoves, while modern biomass can be used for the previous two uses with efficient technologies and for the centralized production of refined energy carriers such as power and heat, as well as biofuels. It is noteworthy that some studies classify biomass that is directly combusted in improved devices such as ICSs and improved kilns (Karekezi et al., 2004) as “improved biomass”.

The methodology presented here focuses on estimating the net reduction of CO_2 emissions (positive or negative) that could be obtained by replacing open fires with ICSs/LPG stoves and displacing fossil fuel power generation (system of reference) with efficient technologies based on thermochemical processes. Two thermochemical processes were evaluated: combustion and gasification. These technologies are the main near term options under development that offer the highest conversion efficiency and lowest technical complexity (Task 33, 2014).

Additionally, it is well known that regions in which traditional biomass consumption is high, there is usually a significant percentage of households (especially in rural areas) that cannot afford electricity/appliances or are not even connected to the grid. Thus, this study considers four “what-if” scenarios that go from improved biomass to modern biomass schemes.

- Scenario 1 (S1): Fuelwood is burnt in ICSs rather than in open fires.
- Scenario 2 (S2): Fuelwood is burnt in ICSs and modern cooking fuels are introduced into the household's fuel portfolio. This assumption is in accordance to the progression suggested by the fuel-device stacking model (Masera et al., 2000).
- Scenario 3 (S3): Fuelwood is processed by dedicated biomass combustion power plants or gasification power plants. Therefore, if all biomass is centralized, fuelwood would no longer be available for households requiring them to switch to other fuels. This paper proposes the use of LPG as a substitute of fuelwood in order to meet household's energy demand. Also, as most of the biomass is usually gathered and consumed in the residential sector (especially in rural areas), this study only considers feasible the deployment of small-medium scale power plants for the production of refined energy carriers.
- Scenario 4 (S4): Fuelwood is burnt in ICSs, LPG is introduced into the household's fuel portfolio and fuelwood is transformed into refined energy carriers in dedicated biomass power plants. This scenario aims to simulate stacking patterns (household accumulation of fuels, and consequently technologies), prioritizing cooking practices and cultural preferences of households.

The four energy systems considered for this study are presented in Figure 2. The economics of adopting these scenarios or the competition by different sectors for biomass are out of the scope of this paper. Nevertheless, it is noteworthy that a strong energy policy would be needed in order to achieve fuel switching, especially in rural communities where economic resources are scarce and there are significant economic, cultural and social barriers to move away from traditional cooking methods.

[Figure 2 about here.]

Despite the potential adverse effects of introducing LPG into the household's fuel portfolio, one of the main benefits of the systems proposed in Figure 2 is that the use of both ICSs and LPG stoves provides households more flexibility to adapt to the specific conditions of each region. Rural areas where people do not have cash incomes and LPG is not available or accessible will remain highly dependent on fuelwood burning in ICSs, while more peri-urban and urban areas will depend more on LPG. The combination of ICSs and LPG stoves also represents the cleanest alternative to traditional biomass. According to a study made by Masera et al. (2000) studying the transition from traditional to modern fuels in rural Mexico, switching from the traditional three-stone cooking stove to an ICS-LPG system reduces the respirable particulate matter and carbon monoxide from 625 μ/m^3 to less than 125 μ/m^3 and 745 $\mathrm{mg/m}^3$ to 2.5 $\mathrm{mg/m}^3$, respectively. With the new generation of ICS currently available, the reduction will be enough to meet the WHO IAP target of 35 μ/m^3 (Ruiz and Masera, 2016).

The net reduction of CO_{2e} emissions (R_N) expressed in kg-C_e/tDM may be calculated as follows

$$R_N = R_G - R_T \tag{1}$$

$$R_T = R_P + R_{CB} + R_{TB} + R_{PT} + R_{FF} \tag{2}$$

where R_G is defined as the gross CO_{2e} reduction per tonne of dry biomass. That is, the CO_{2e} emissions that could be avoided by switching from open fires to a more efficient technology taking into account the non-renewable fraction of fuelwood use (fNRB). R_T is defined as the total CO_2 released during biomass power generation and comprises five processes (partly based on Ogi and Dote (2003) methodology):

1. CO_{2e} released during biomass production (R_P), establishment (R_e) to harvest (R_h).
2. CO_{2e} released from collection of harvested biomass (R_{CB}).
3. CO_{2e} released from transporting biomass to the power plant (R_{TB}).
4. CO_{2e} released during the pretreatment of biomass for power generation (R_{PT}).
5. CO_{2e} released from households burning LPG instead of fuelwood (R_{FF}).

The units of R_N, R_G, R_T, R_P, R_{CB}, R_{TB}, R_{PT}, and R_{FF} are kilograms of C equivalent per tonne of dry biomass [kg-C_e/tDM]. It is important to mention that this study only considers the more restricted set of Kyotosanctioned gases (CO_2 and CH_4).

From here onwards, the parameters used as input data for the calculation of R_N are described. With respect to the biomass origin, three land-scenarios were evaluated: woodlands, native forests and fuelwood plantations. In the first scenario, it was assumed that every year, both dead trees and fallen timber from the woodlands are collected. In the second scenario, it was assumed that fuelwood is annually collected from the native forest floor and also stem, bark and branch material from dead trees. In the third scenario, it was assumed that a coppiced plantation is grown only for fuelwood production. Table 1 presents the main parameters to estimate R_P for the different land types from which biomass can be extracted. That is, biomass yield (Y), standing period of biomass (S) and CO_2 released during establishment (R_e) to harvest (R_h).

[Table 1 about here.]

The CO_2 released during biomass production was estimated based on equation 3:

$$R_P = R_e + R_h \tag{3}$$

It was considered an average value for R_h of 4 kg-C_e/tDM (Table 1), in accordance to a study made by CSRIO (2003). The R_h value varies depending on the harvest system selected, i.e., small scale harvest (6.1 kg-C_e/tDM) or commercial harvest (2.8 kg-C$_e$/tDM) (CSRIO, 2003). On the other hand, the value of R$_e$ is zero for woodlands and native forests (Table 1) because it was considered that these plots were already established.

The input data used in the present study to estimate R$_{CB}$, R$_{TB}$, R$_T$ and R$_G$ are tabulated in Table 2.

[Table 2 about here.]

The CO$_2$ released from the collection of harvested biomass (R$_{CB}$) was determined with

$$R_{CB} = \frac{C_{CB}\ D_a\ L_{CB}}{A\ Y} \tag{4}$$

The loading capacity of the truck (L$_{CB}$) was set at 8 tDM. The CO$_{2e}$ release unit of the tractor (C$_{CB}$) was considered to be 0.1 kg-C$_e$/tDM/km. D$_a$ is defined as the distance for annual collection of biomass and A, the area of the plantation with an inner radius R$_o$. These parameters were estimated based on Ogi and Dote (2003) methodology.

The CO$_2$ released from transporting the biomass to the power plant (R$_{TB}$) was calculated using

$$R_{TB} = C_{TB}\ D_{TB} \tag{5}$$

Based on a small-medium scale power plant scenario, the distance of transport to the power plant (D_{TB}) was set at 50 km. This value is in accordance with (CSRIO, 2003), which indicates that this is the normal distance to transport fuelwood from the source to the consumer for small-scale systems. The CO_{2e} released by the vehicle transporting the biomass to the power plant (C_{TB}) was set at 0.4 kg-C_e/tDM/km.

The gross CO_{2e} reduction (R_G) was estimated based on equation 6, 7 and 12, depending on the scenario under study (see Figure 2). In equation 6-12, the subscript notation OF/B, ICS/B and TP/oil refers to open fires burning biomass, ICSs burning biomass and conventional fossil fuel power plants, respectively. Meanwhile, the subscript PP/B indicates the biomass power plant type and therefore, depending on which conversion technology is used, PP/B can change to CP/B referring to biomass combustion power plants or GP/B referring to biomass gasification power plants. The arrow symbol in each of the subscripts points the switch of a technology. Further, in order to avoid overestimating the potential reduction in CO_{2e} emissions, it was considered an fNRB value of 30% in accordance with Bailis et al. (2015).

- Scenario 1:

$$R_G = R_{OF/B \rightarrow ICS/B} = \theta_{OFR/B}\ (1 - fNRB)\ H_B \left[1 - \frac{\eta_{OF/B}}{\eta_{ICS/B}}\right] + \theta_{OFNR/B}\ (fNRB)\ H_B \left[1 - \frac{\eta_{OF/B}}{\eta_{ICS/B}}\right] \quad (6)$$

- Scenario 2: The value for R$_G$ can be estimated using equation 6 because the technology to transform biomass is the same as in scenario 1 (i.e., ICSs). The CO$_{2e}$ released by burning LPG is included in R$_{FF}$.

- Scenario 3:

$$R_G = R_{OF/B \to PP/B} + R_{TP/oil \to PP/B} \tag{7}$$

$$\begin{split} R_{OF/B \to PP/B} = \theta_{OFR/B}\ (1 - fNRB)\ H_B \left[1 - \frac{\eta_{OF/B}}{\eta_{PP/B}}\right] \\ + \theta_{OFNR/B}\ (fNRB)\ H_B \left[1 - \frac{\eta_{OF/B}}{\eta_{PP/B}}\right] \end{split} \tag{8}$$

$$R_{TP/oil \to PP/B} = \theta_{TP/oil}\ H_B \left[\frac{\eta_{PP/B}}{\eta_{TP/oil}}\right] \tag{9}$$

- Scenario 4: Aims to simulate stacking patterns. That is, where multiple technologies and fuels are available in the energy system to meet certain energy needs. Therefore, the total R$_G$ for scenario 4 can be defined as the sum of the gross CO$_{2e}$ reduction (R$_G$) defined for scenarios 1 and 3. The expressions to estimate R$_{OF/B \to ICS/B}$, R$_{OF/B \to PP/B}$ and R$_{TP/oil \to PP/B}$ for scenario 4 can be extracted from equation 6, 8 and 9.

$$R_G = R_{OF/B \to ICS/B} + R_{OF/B \to PP/B} + R_{TP/oil \to PP/B} \quad (10)$$

R_G was calculated using a low heating value (H_B) for fuelwood of 16 GJ/tDM, while emission factors assuming renewable use ($\theta_{OFR/B}$) and non-renewable use ($\theta_{OFNR/B}$) in open fires were set at 2.5 kg-C_e/GJ and 28.8 kg-C_e/GJ, respectively (Johnson et al., 2009). The emission factor for fossil-fuel power plants ($\theta_{TP/oil}$) was assumed to be 28 kg-C_e/GJ.

With regards to efficiency, the efficiency of open fires ($\eta_{OF/B}$) was set to 10% (Bhattacharya et al., 2002), while for the ICSs it was assumed an efficiency of 29% (Chan et al., 2015). On the other hand, the electric efficiency of the oil power plants ($\eta_{TP/oil}$) was set at 39%, while for the power plants processing biomass, the electric efficiency ($\eta_{CP/B}$ and $\eta_{GP/B}$) was obtained from regression curves based on commercial systems in operation (Figure 3).

[Figure 3 about here.]

This study also investigates the CO_2 emission reduction that could be achieved by further application of combined heat and power (CHP) systems. Figure 4-(a) and Figure 4-(b) present the overall efficiency of biomass CHP plants based on combustion and gasification, respectively. The solid line is the fitting curve for the values obtained from literature. Here, the overall efficiency is defined as the sum of the electrical power output and useful heat output over the total fuel input.

[Figure 4 about here.]

With respect to the plant scale (C_A), for scenario 3, the base case value for the biomass combustion power plants was set at 10 $MW_{th-input}$. This value is in accordance with data presented by IPCC (2011) for direct combustion of wood log, residues, chips and agricultural wastes. The reference value for the scale of the biomass gasification power plants (C_A) was set to 0.3 $MW_{th-input}$. This value is in accordance to recent data available related to the smallest downdraft gasifier coupled with a gas engine (DG/GE) under operation (Electrolabel, Belgium and Wallonia Municipalities) (Task 33, 2014).

With regards to the plant scale for scenario 4, it was considered that ICSs have a penetration rate of 50%. In other words, power plants could only access 50% of the biomass available in scenario 3 consequently reducing their capacity in half. That is, 5 $MW_{th-input}$ for biomass combustion power plants and 0.15 $MW_{th-input}$ for biomass gasification power plants. These values are in accordance with Bauen et al. (2009), who indicates that there are a growing number of viable biomass combustion plants and gasification plants that range from 5 to 10 $MW_{th-input}$ and from 0.1 to 1 $MW_{th-input}$, respectively.

To evaluate the last two terms of equation 2, R_{PT} and R_{FF}, the CO_{2e} released during the pretreatment of biomass for power generation (R_{PT}) was set at 7 kg-C_e/tDM (Dote et al., 2008). Meanwhile, the CO_{2e} released by burning LPG was determined with

$$R_{FF} = \theta_{FF}\ H_B \tag{11}$$

It was assumed that LPG has an average emission factor (θ_{FF}) of 18 kg-C$_e$/GJ. The value of H$_B$ was set to 16 GJ/tDM.

Finally, we estimate the potential net reduction in CO$_2$ emissions (expressed in Mt of CO$_{2e}$) for year 2050. This calculation was performed using data reported by Smeets and Faaij (2007) regarding the global bioenergy potential from forestry in 2050 and the R$_N$ values obtained for scenario 4 (see Figure 6). The projection provided by Smeets and Faaij (2007) was obtained by comparing the future demand with the future supply of industrial roundwood and fuelwood. For the present calculation, we only take into account the projected biomass coming from surplus growth forest and logging residues reported by Smeets and Faaij (2007). Estimates by Smeets and Faaij (2007) for the future biomass production were presented for five different scenarios: (I) theoretical, considers the maximum wood production potential of forests; (II) technical, includes the wood production taking into account the potential technical barriers (e.g., steepness of terrain); (III) economical, considers the technical potential that could be produced at economically profitable level; (IV) ecological, includes the theoretical potential taking into account criteria such as biodiversity and soil erosion and (V) economical-ecological, considers a criterion to prevent a further decrease of biodiversity in undisturbed forests.

In order to put these results into context, the potential net reduction in CO_{2e} emission in 2050 has been compared to the amount of emissions that could be released to the atmosphere if all biomass available in 2050 was burnt in open fires:

$$E_{OF/B2050} = M_{2050}\ \theta_{OFR/B}\ (1 - fNRB) + M_{2050}\ \theta_{OFNR/B}\ fNRB \tag{12}$$

Where M_{2050} refers to amount of biomass projected for year 2050.

3. Results

Biomass, if used sustainably and transformed by low-carbon and efficient conversion technologies, can lead to a net CO_2 emission reduction. The CO_2 abatement potential by using high efficiency technologies to transform fuelwood into refined energy carriers is presented from here on. Values for the gross CO_2 reduction (R_G) are only presented for the scenario where biomass is obtained from woodlands due to R_G is not influenced by the origin of the biomass (section 2). Any specific changes related to the origin of biomass are taken into account in the CO_2 emissions released during biomass power generation, R_T (equation 2, section 2). For illustration purposes, values for R_T (grey bars) have been plotted on the negative side of the axis to distinguish them from the reduction in CO_2 emissions.

3.1. Dispersed biomass energy systems

[Figure 5 about here.]

Figure 5 presents the net reduction in CO_{2e} emissions for scenarios one, two and three. According to Figure 5, the introduction of efficient technologies such as ICSs (S1) to replace open fires would allow an average[1] net CO_2 reduction ($\overline{R_N}$) of 105 kg-C_e/tDM (R_{FF}=0). Unlike S1, in the case where both ICSs and modern cooking fuels are introduced into the household's fuel portfolio (S2), the amount of carbon that could be offset by S2 is negative (green bars with red border). In other words, the system will no longer provide a reduction in CO_2 emissions. This is attributed to the assumption of an energy penalty related to burning modern cooking fuels (section 2), which provides a scenario where the amount of carbon released by the production of biomass and the use of LPG ($\overline{R_T}$ = -260 kg-C_e/tDM, gray bar) is higher than the amount of carbon that could be offset ($\overline{R_G}$ = 109 kg-C_e/tDM, purple bar). Thus, scenario 2 will be emitting 151 kg of C equivalent per every tonne of biomass burnt (see negative axis in Figure 5, green bar with red border). On the other hand, if it is considered a scenario where instead of replacing open-fires by ICSs, biomass is processed in dedicated biomass power plants (displacing fossil fuel power generation), and households instead of using fuelwood use LPG, an average net CO_2 reduction of 7 kg-C_e/tDM (S3-C, green bar) could still be obtained when using 10 MW combustion power

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[1] ($\overline{R_N}$)= Average of scenario for woodlands, native forest and fuelwood plantations.

plants or 10 kg-C_e/tDM (S3-G, green bar) when using 0.3 MW gasification power plants.

3.2. Fuel-Device Stacking systems

Figure 6 shows the reduction in CO_2 emissions that could be obtained in a hypothetical scenario where there is stacking of fuels and technologies. In other words, where ICSs, LPG stoves and dedicated biomass power plants coexist in the same system.

[Figure 6 about here.]

As can be seen in Figure 6, the assumption that multiple devices and fuels are used to satisfy household's energy needs (S4) still yields a net reduction in CO_{2e} emissions. It is estimated that the average gross amount of carbon that could be offset ($\overline{R_G}$) by the use of ICSs, LPG stoves and combustion plants is about 376 kg-C_e/tDM (S4-C; sum of purple, light blue and light red bars). Meanwhile, if instead of using biomass combustion plants, gasification plants are introduced, values for $\overline{R_G}$ would be around 397 kg-C_e/tDM (S4-G; sum of purple, light blue and light red bars). Subtracting the carbon released by the production of biomass and the use of LPG (gray bar), a net CO_{2e} reduction of 84 kg-C_e/tDM could be obtained when deploying combustion plants (S4-C, green bar) or 105 kg-C_e/tDM when using gasification plants (S4-G, green bar).

3.3. *Electricity-only to CHP plants: influence of the overall efficiency*

Figure 7 presents the net CO_2 reduction (R_N) for scenarios one, two and three in case dedicated biomass power plants in Figure 5 and Figure 6 are replaced or converted from electricity-only to CHP plants. In case dedicated biomass power plants in Figure 5 and Figure 6 are replaced or converted from electricity-only to CHP plants, higher values for the net CO_2 reduction (R_N) are observed (see Figure 7).

[Figure 7 about here.]

Results show that the deployment of CHP plants lead to a mean gross CO_{2e} reduction ($\overline{R_G}$) of 1027 kg-C_e/tDM (S3-C, sum of purple and light red bars) when using power plants based on combustion or 992 kg-C_e/tDM (S3-G, sum of purple and light red bars) when using CHP plants based on gasification. The mean value for $\overline{R_T}$ for all scenarios is around 287 kg-C_e/tDM (gray bar). Thus, it is estimated that the average net CO_2 reduction ($\overline{R_N}$) that could be achieved by adopting biomass CHP plants would amount to 740 kg-C_e/tDM for 10 $MW_{th-input}$ combustion plants (S3-C, green bar) and 705 kg-C_e/tDM for 0.3 $MW_{th-input}$ gasification plants (S3-G, green bar). It should be noted that in practice, CHP systems are not always feasible as demand for heat is not always required.

For the stacking scenario, the results shown in Figure 8 indicate that it might be possible to achieve a 1130 kg-C_e/tDM mean gross CO_{2e} emission reduction ($\overline{R_G}$) when using ICSs, LPG stoves and CHP plants based on combustion (S4-C, sum of purple, light blue and light red bars), while a 1103 kg-C_e/tDM gross CO_{2e} reduction when using ICSs, LPG and CHP plants based on gasification (S4-G, sum of purple, light blue and light red bars).

[Figure 8 about here.]

Even though this scenario considers stacking patterns, it is estimated that a mean net reduction in CO_2 emissions of 839 kg-C_e/tDM could be achieved when using ICSs, LPG stoves and CHP plants based on combustion (S4-C, green bar). In case of gasification CHP plants, a 811 kg-C_e/tDM net reduction in CO_2 emissions could be obtained for scenario S4-G conditions (green bar).

3.4. From traditional to modern biomass: projected reduction in CO_2 emissions through 2050

Finally, in order to put in perspective the results obtained in this work, Figure 9 gives an overview of the projected net reduction in CO_{2e} emissions that could be achieved if instead of using the potential biomass available in 2050 (Smeets and Faaij, 2007) as traditional biomass, a system as the one presented in scenario 4 is implemented (Figure 6). That is, using ICSs, LPG cooking stoves and dedicated biomass power plants. The potential net reduction of CO_{2e} emissions for the year 2050 was calculated by multiplying the amount of biomass projected for the year 2050 by the average R_N obtained for the stacking scenario. Thus, for the scheme where ICSs, LPG cooking stoves and combustion power plants are used, the value of $\overline{R_N}$ was set to 84 kg-C_e/tDM (Figure 6, S4-C). Meanwhile, for the scenario where ICSs, LPG cooking stoves and gasification power plants are deployed, the potential net CO_{2e} reduction ($\overline{R_N}$) was fixed at 105 kg-C_e/tDM (Figure 6, S4-G). Results for Latin America & Caribbean (LAC & C) are also presented as according to Smeets and Faaij (2007) this region will be the most promising wood supplier in 2050. Values presented in Figure 9 are expressed in Mt of CO_{2e}/yr.

[Figure 9 about here.]

According to Figure 9, if the biomass projected for 2050 is burnt in open fires, taking into account the fNRB, the global CO_{2e} emitted to the atmosphere based on the theoretical, technical, economical, economical-ecological and ecological potential of wood supply would be 2347 Mt of CO_{2e}, 2148 Mt of CO_{2e}, 643 Mt of CO_{2e}, 159 Mt of CO_{2e} and 428 Mt of CO_{2e}, respectively (Figure 9, light red bars). Values for LAC & C are projected to be in the rage of 15 Mt of CO_{2e} (economical-ecological potential) to 799 Mt of CO_{2e} (theoretical potential).

Using the R_N values obtained for the stacking scenario (Figure 9, S4-C, green bars), the expected net reduction in global CO_{2e} emissions would be in the range of 80 Mt of CO_{2e} (ecological-economical potential) to 1181 Mt of CO_{2e} (theoretical potential). The reduction of CO_{2e} emissions in LAC & C would be between 8 Mt of CO_{2e} (economical-ecological potential) and 402 Mt of CO_{2e} (theoretical potential).

Lastly, the global net CO_{2e} reduction in case biomass is processed under

S4-G conditions is between 100 Mt of CO_{2e} (ecological-economical potential) and 1476 Mt of CO_{2e} (theoretical potential). Values for LAC & C are projected to be in the range of 10 Mt of CO_{2e} (economical-ecological potential) to 502 Mt of CO_{2e} (theoretical potential).

3.5. Sensitivity analysis

As the results presented for the net CO_{2e} reduction (R_N) are sensitive to the parameters assumed in this work (e.g., biomass yield, distance to the power plant, efficiency and fNRB), a sensitivity analysis was conducted. As an example, the sensitivity test was made for scenario 4 (stacking) conditions using biomass coming from native forests only. This is due to scenario 4 is the one that has more similarities to a real-life system where multiple technologies and fuels are available. That is, using ICSs and LPG stoves to meet the demand of the residential sector and dedicated biomass power plants for electricity generation. With respect to the origin of the biomass, fuelwood from native forests was selected as fuel because this type of biomass was the one that reported the highest CO_2-emissions mitigation for all scenarios considered in this study. A sensitivity analysis for the case when the electrical efficiency is replaced by the overall efficiency was not performed, as simliar trends would have been obtained.

[Figure 10 about here.]

As can be seen in Figure 10-a, the influence of the efficiency of the biomass power plants on R_N is strong. If the efficiency of the biomass combustion power plants is increased by 1%, the net reduction of CO_{2e} emissions rises up to 87 kg-C_e/tDM (set value, R_N = 84 kg-C_e/tDM). In case of gasification power plants, if the efficiency is increased by 1%, the net reduction of CO_{2e} emissions increases up to 108 kg-C_e/tDM (set value, R_N = 105 kg-C_e/tDM).

With respect to the biomass yield (Figure 10-b), the sensitivity analysis indicates that the biomass yield has very little influence on R_N. If yields increase up to 12 t/ha/y (around 240% variation), the value of R_N only increases up to 84.6 kg-C_e/tDM for the ICS/LPG stove/biomass combustion power plant configuration and 105.2 kg-C_e/tDM when using gasification-based power plants. On the other hand, R_N is very sensitive to the LHV of biomass. A 10% increase in the LHV of biomass would increase the value of R_N to 96 kg-C_e/tDM for the scheme using biomass combustion power plants and 119 kg-C_e/tDM for the configuration using gasfication power plants.

With respect to the transportation distance (D_{TB}, Figure 10-c), the impact of D_{TB} on R_N is moderate. For an additional 20 km distance, the reduction of CO_{2e} emissions is cut down by 4 kg-C_e/tDM for both combustion and gasification power plants configurations.

Finally, it can be seen that R_N is very sensitive to the non-renewable fraction of fuelwood (fNRB, Figure 10-d). If the fNRB increases from 0.30 to 0.35, the net reduction of CO_2 emissions rises up to 108 kg-C_e/tDM for the combustion scheme and 130 kg-C_e/tDM for the ICS/LPG stove/biomass gasification power plant configuration.

4. Discussion

The main benefit of using modern biomass in traditional biomass intensive countries is that "low-cost" and "clean" energy carriers can be produced from local resources that are already being collected. This demands the need to foresee systems capable of offering a wide portfolio of energy carriers depending on the needs of the end-users and the matureness of the biomass infrastructure. This study estimates the abatement potential of different CO_2 reduction technologies with wide differences in the scale of complexity, from ICSs to gasification power plants. These systems aim to provide a portfolio of options for biomass intensive countries affected by indoor pollution resulting from traditional biomass, while achieving a net reduction in CO_2 emissions.

4.1. Transitioning from open fires to ICSs and LPG stoves

In the short-term it is clear that cooking fuels and ICSs will have to play a more important role in biomass intensive countries due to their low complexity. Although both technologies represent a healthier alternative to open fires, in CO_2 mitigation terms, implementing only ICSs and LPG stoves do not deliver all the potential benefits. This is clearly illustrated by the R_N values obtained for scenario 2 which indicate that there would be a net increase of CO_2 emissions instead of a reduction in the environmental impacts of bioenergy use when both ICSs and LPG stoves are implemented. At the same time, under scenario 2 conditions, no further use of the saved biomass in modern systems will be encouraged. In practice, scenario 2 may become an imperfect substitute to traditional biomass because it has been observed (Masera et al., 2015) that open fires are used for different tasks than those that could be provided by both ICSs and LPG stoves, and thus leading to stacking. For instance, studies show that stacking of stoves (open fires and gas stoves) is still a current practice in Mexico 27 years after the introduction of LPG (Masera et al., 2000) and persists even when such fuels are heavily subsidized, as in the case of Indonesia (Andadari et al., 2014). Also, a study by Ruiz-Mercado et al. (2011) evaluating the adoption and sustained used of ICSs in Mexico's highlands showed that after the adoption of ICSs only 10% of the households abandoned open fires completely. If electricity from biomass is added to the energy mix, then the needs for continuing using the open fires would be reduced and mitigation will be increased.

4.2. Transitioning from open fires to ICSs, LPG stoves and biomass power plants

The scenario that reports the highest net reduction of CO_{2e} emissions (R_N) is the stacking scenario, either when combustion or gasification power plants are used. This is mainly attributed to the displacement of fossil fuel power generation and the assumption that the native forests are already established, setting the value of R_P (CO_{2e} released during biomass production) to zero. There is, however, a slight difference in the R_N values among the aforementioned technologies (combustion or gasification) and this is attributed to the efficiency of the gasification plants. On the other hand, from the biomass user's perspective, the stacking scenario is the most promising as it considers the production of different energy carriers catering to different energy needs.

Finally, according to the findings presented in Figure 7 and Figure 8, it is clear that energy systems perform better when they are oriented to produce high value energy carriers from biomass, such as the production of heat and power. Results indicate that there is a significant potential for near-term CO_2 reduction from biomass CHP plants, but their implementation in traditional biomass intensive countries will be highly dependent on whether or not there is a heat demand.

4.3. Degree of influence and sensitivity analysis

Results of the sensitivity analysis indicate that the main driving factors for CO_2 reduction are technology efficiency and fNRB. An increase in efficiency is accompanied with increases in the net reduction of CO_{2e} emissions. For instance, per every 1% increase in electrical efficiency, in average, 3 kg-C_e/tDM could be reduced by implementing the conditions of the stacking scenario. On the other hand, if the fNRB rises from 0.30 to 0.35, the value of R_N increases by 20%. These results therefore emphasize not only the importance of considering the fNRB, but also the relevance of assuming a modest value of fNRB when this cannot be extracted from field studies to avoid overestimating the CO_2 savings.

Yield was another parameter that influenced R_N, in less extent than efficiency and fNRB, but enough to establish a difference between systems that use biomass from native forests as fuel from systems that use either biomass coming from woodlands or fuelwood plantations. Further, it is important to mention that changes in the transportation distance (D_{TB}) are not significant here because this analysis only considers scenarios with small/medium scale plants under a short distance transportation scheme. Thus, if larger power plants are deployed, the D_{TB} parameter will play a more important role as longer transport distances will be required, increasing significantly the CO_2 emissions.

4.4. Global impacts of traditional biomass emissions

With regards to the projected net reduction in CO_2 emissions in 2050, even under the most strict of the scenarios projected by Smeets and Faaij (2007), the economical-ecological scenario, it is estimated that the implementation of the ICSs/LPG stove/combustion power plant configuration could provide a global net CO_2 reduction of 80 Mt of CO_{2e}, while the use of the ICSs/LPG stove/gasification power plant scheme reports a global net CO_2 reduction of 100 Mt of CO_{2e} (see Figure 9). Nevertheless, several studies suggest that phasing out traditional biomass will be a difficult task specially in countries which have large domestic resources of biomass and low economic development. This highlights how challenging it will be to replace traditional biomass with modern biomass, since leaving three-stone cooking fires will represent significant stranded assets. Thus, successful implementation of modern biomass systems in traditional biomass intensive countries will strongly depend on local policies. Governments and policy makers have to realize that in order to evade an underutilization of biomass there must be a diversification of biomass resources/technologies, institutional strengthening and long-term policy commitments.

Energy mixes highly dependent on one major fuel such as fuelwood represent a policy opportunity to encourage and support the exploitation of other biomass feedstocks for the production of refined energy carriers (Cutz and Santana, 2014). Expanding the use of modern biomass in traditional biomass intensive countries should involve the development of entire biomass chains including land-use transformations, establishment of biomass supply-chain infrastructures, development of new conversion technologies and establishment of new markets for biomass based products (Cutz et al., 2016). Furthermore, considering that traditional biomass consumption is an indicator of unmet demand for more efficient fuel (Roy, 2000), it can be stated that there is a market of sufficient size equivalent to the percentage of the population in biomass intensive countries who lack access to modern fuels and technologies. Thus, modern biomass systems in regions dependent on traditional biomass provide a field of opportunity for different sectors, especially for developers in the manufacturing process and investors/stakeholders in the clean cooking and power sectors.

Evidence also indicates that institutions play a key role when supporting green energy policies in countries with abundant natural resources. Thus, when institutions are weak, that is, having high levels of bureaucracy and corruption, institutions are unable to take full advantage of the natural resources (Mehlum et al., 2006). Therefore, the expansion of modern biomass will highly rely on how traditional biomass intensive countries manage to make an efficient use of resources to invest in fuel switching and efficient technologies.

Finally, it is important to highlight that besides the importance of achieving a reduction of CO_2 emissions in traditional biomass intensive countries, the main concern is to reduce indoor air pollution as the exposure to the smoke and particulate matter from the use of traditional biomass leads to severe health problems.

5. Conclusions

The problems related to the use of traditional biomass, such as forest degradation (if wood is extracted faster than it can be regenerated), forced resettlement of nearby communities and indoor air pollution are well known. Clearly, these problems are more severe in traditional biomass intensive countries, where this resource is used to produce energy carriers through low-efficient processes, e.g., burning fuelwood in open-fires. The intensity in which this practice occurs demand actions to design systems capable of switching the traditional biomass consumption of countries that are endowed with abundant biomass resources to what is called the "sustainable development pathway".

This study proposes and evaluates several schemes to switch from traditional to modern biomass systems in biomass intensive countries. Nevertheless, results show that not all fuel-technology combinations result in lower emissions than traditional biomass systems. The results from this analysis indicate that despite burning a modern cooking fuel and centralizing fuelwood, a net reduction of CO_2 emissions could be achieved in all scenarios, except for scenario 2. Results obtained for scenario 2 where both ICSs and LPG stoves are implemented indicate that there would be a net increase of CO_2 emissions instead of reducing the environmental impact. All these suggest that countries should prioritize developing infrastructures that could help complement and maximize the use of the available resources. In this sense, electricity production from biomass is a good option for diversifying and adding value to energy carriers in traditional biomass intensive countries. The creation of small cooperatives handling the biomass and supplying the biomass market might be a feasible option to achieve modern biomass systems. Larger structures as cooperatives are also more exposed to access financing, cooperation and knowledge transfer than spread households, which is crucial when implementing new technologies.

On the other hand, results of this paper strengthen the evidence base to consider fuel stacking a long-term strategy rather than a transient state. A strategy where the total environmental impact could still be reduced if well-designed systems are implemented. According to the results obtained for the stacking scenario, it is estimated that a net reduction of 84 kg-C_e/tDM could be obtained when deploying ICSs and LPG stoves to meet the demand of the residential sector, and electricity is produced in power plants based on biomass combustion. Meanwhile, a net reduction of 105 kg-C_e/tDM could be obtained for the ICS/LPG stove/gasification power plant system. Notice that under these schemes cleaner fuel and technologies would be available for households, while at the same time households would increase their options for meeting their energy needs.

Finally, based on the demand of fuelwood and industrial roundwood in 2050, it is projected that if all bioenergy (economical-ecological potential) is used as modern biomass, a global CO_2 reduction of 80 Mt of CO_{2e} or 100 Mt of CO_{2e} could be achieved by the implementation of the ICS/LPG stove/combustion power plant or ICS/LPG stove/gasification power plant scheme, respectively.

Notation

A= area of the plantation [km^2];

C_A= installed capacity [MW];

C_{CB}= CO_{2e} release unit of the tractor [kg-C_e/tDM/km];

C_{TB}= CO_{2e} release by the vehicle transporting the biomass to the power plant [kg-C_e/tDM/km];

D_a= distance for annual collection of biomass [km];

D_{TB}= distance of transport to the power plant [km];

$E_{OF/B2050}$= emissions that could be released to the atmosphere if all biomass available in 2050 was burnt in open fires [Mt of CO_2e];

$fNRB=$ fraction of non-renewable fuelwood use;

$H_B=$ low heating value [GJ/tDM];

$L_{CB}=$ loading capacity of the truck [tDM];

$M_{2050}=$ amount of biomass projected for the year 2050 [t];

$R_e=$ CO_{2e} released during establishment [kg-C_e/tDM];

$R_{CB}=$ CO_{2e} released by collection of harvested biomass [kg-C_e/tDM];

$R_{FF}=$ CO_{2e} released by households burning LPG instead of fuelwood [kg-C_e/tDM];

$R_G=$ gross CO_{2e} reduction [kg-C_e/tDM];

$R_h=$ CO_{2e} released during harvest [kg-C_e/tDM];

$R_N=$ net reduction of CO_{2e} emissions [kg-C_e/tDM];

$R_o=$ inner radius of the plantation [km];

$R_P=$ CO_{2e} released during biomass production [kg-C_e/tDM];

$R_{PT}=$ CO_{2e} released during the pretreatment of biomass for power generation [kg-C_e/tDM];

$R_T=$ total CO_2 released during biomass power generation [kg-C_e/tDM];

$R_{TB}=$ CO_{2e} released by transporting biomass to the power plant [kg-C_e/tDM];

$S=$ standing period of biomass [year];

$Y=$ biomass yield [t/ha/year];

Greek

$\eta_{OF/B}=$ efficiency of open fires;

$\eta_{TP/oil}$= efficiency of oil power plants;

$\eta_{CP/B}$= efficiency of biomass combustion power plants;

$\eta_{GP/B}$= efficiency of biomass gasification power plants;

$\theta_{OFR/B}$= Emission factors assuming renewable use in open fires [kg-C_e/GJ];

$\theta_{OFNR/B}$= Emission factors assuming non-renewable use in open fires [kg-C_e/GJ];

$\theta_{TP/oil}$= Emission factors fossil-fuel power plants [kg-C_e/GJ];

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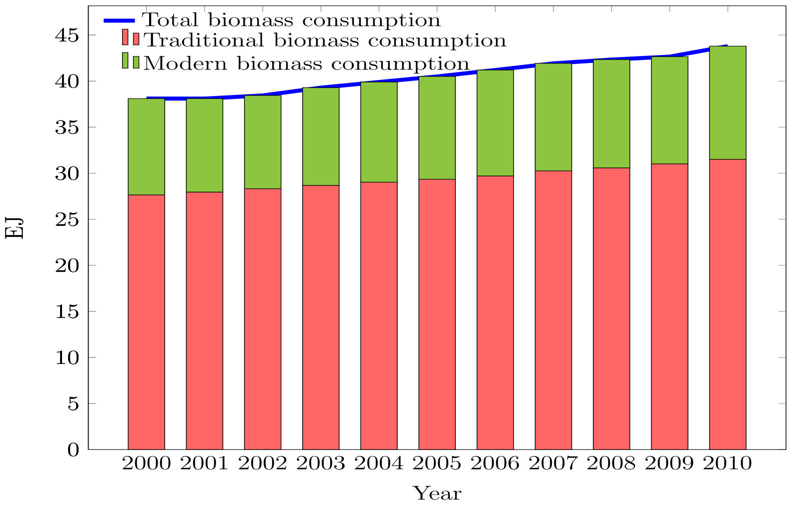
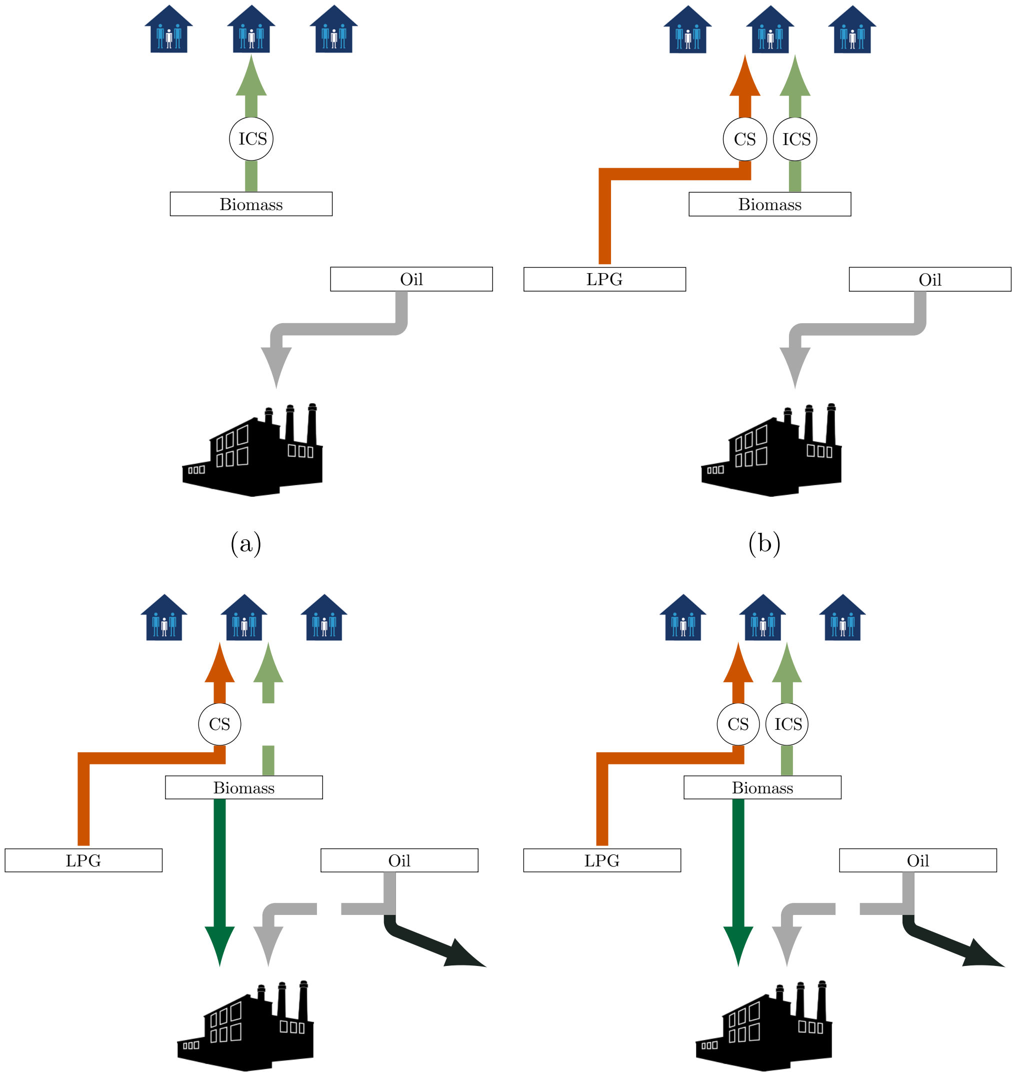
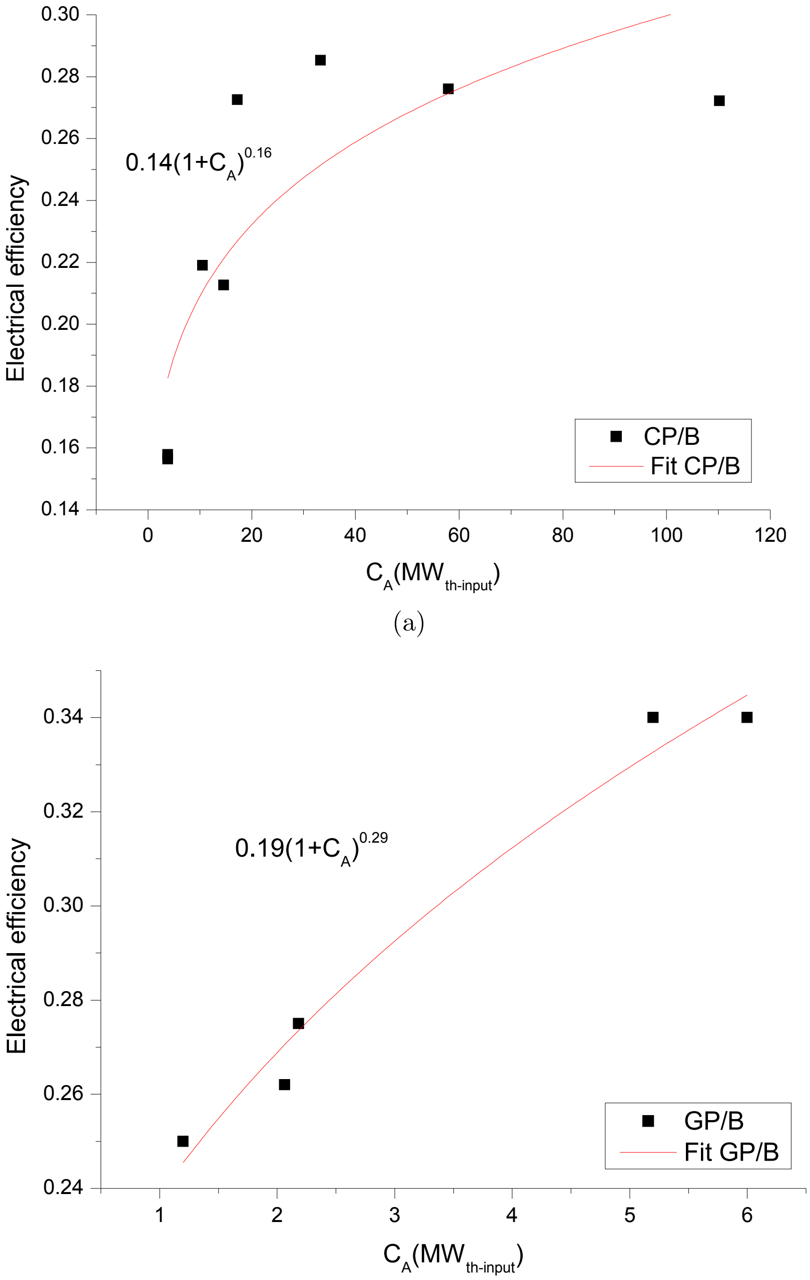


Figure 1: World biomass consumption. Note: Data was extracted from World Bank (2016). Traditional biomass is defined as biomass used in the residential sector, while modern biomass is defined as biomass used for the production of heat and power.



(a) (b) (c) (d)

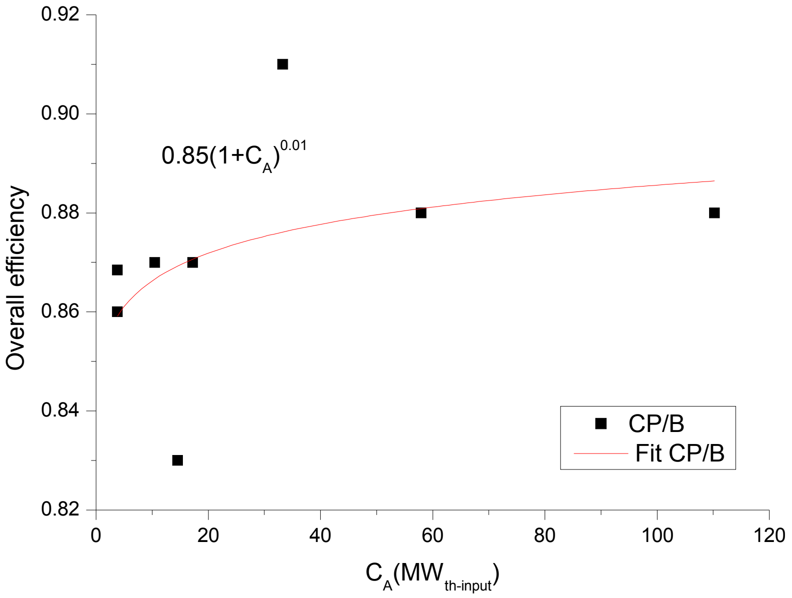
Figure 2: Schematic diagram of the energy systems considered for evaluation. (a) scenario 1, ICSs; (b) scenario 2, ICSs and LPG stoves; (c) scenario 3, LPG stoves and dedicated biomass power plants (No ICSs); and, (d) scenario 4, stacking (ICSs, LPG stoves and dedicated biomass power plants).



(a)

(b)

Figure 3: Relationship between electrical efficiency and installed capacity for the CP/B (a) and GP/B (b) configuration. Source: Data was extracted from Task 33 (2014).



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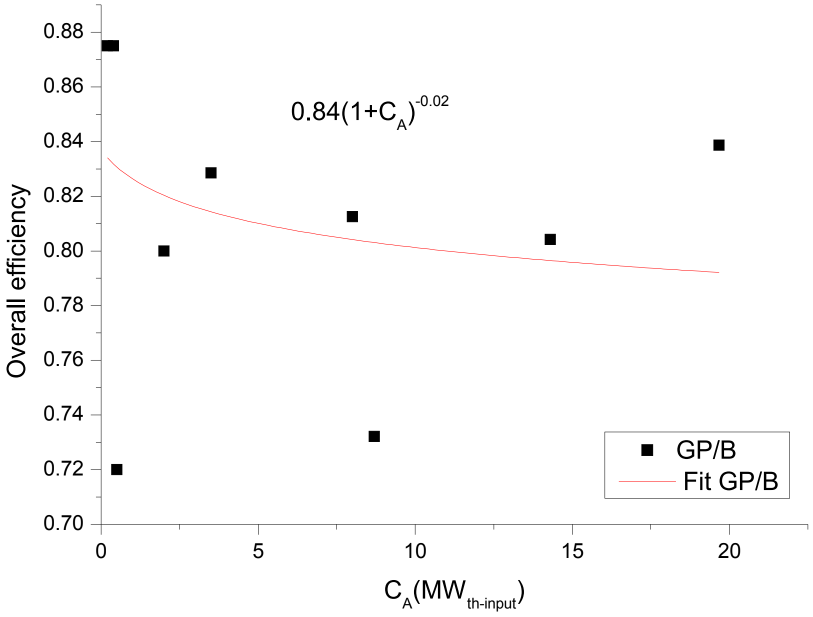


(b)

Figure 4: Relationship between overall efficiency and installed capacity for the CP/B (a) and GP/B (b) scheme. Source: Data was extracted from Task 33 (2014).

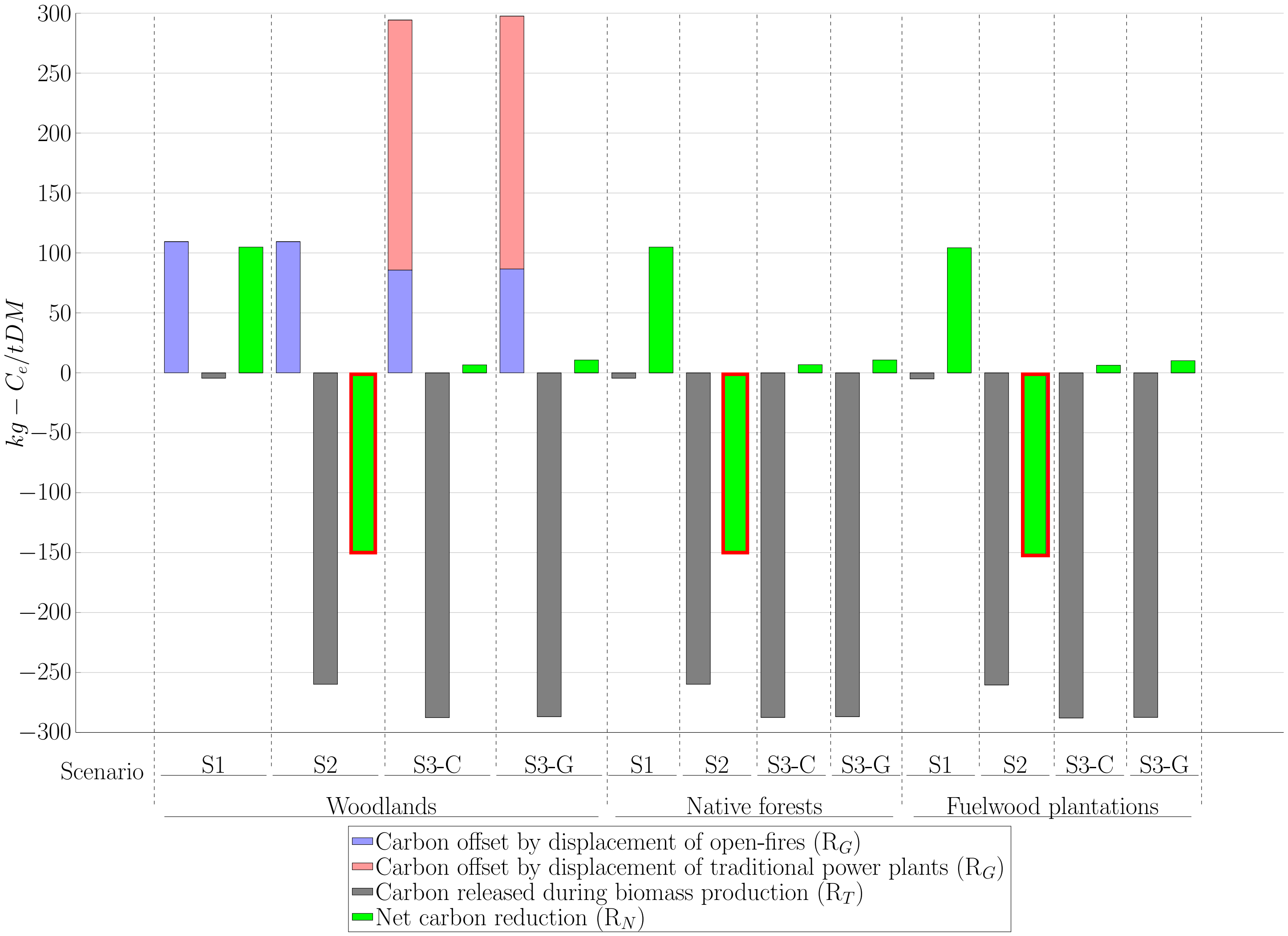


Figure 5: Net reduction in CO_{2e} emissions (R_N, green bars) by deployment of ICSs, LPG stoves and biomass power plants (scenario 1, 2 and 3). Note: R_G is defined as the gross CO_{2e} reduction per tonne of dry biomass. R_T refers to the CO_{2e} released by the production of biomass (grey bars) and use of LPG as cooking fuel (scenario 2 and 3). The green bars with red border indicate that there is no net reduction in CO_2 emissions, the system is emitting CO_2 to the atmosphere.

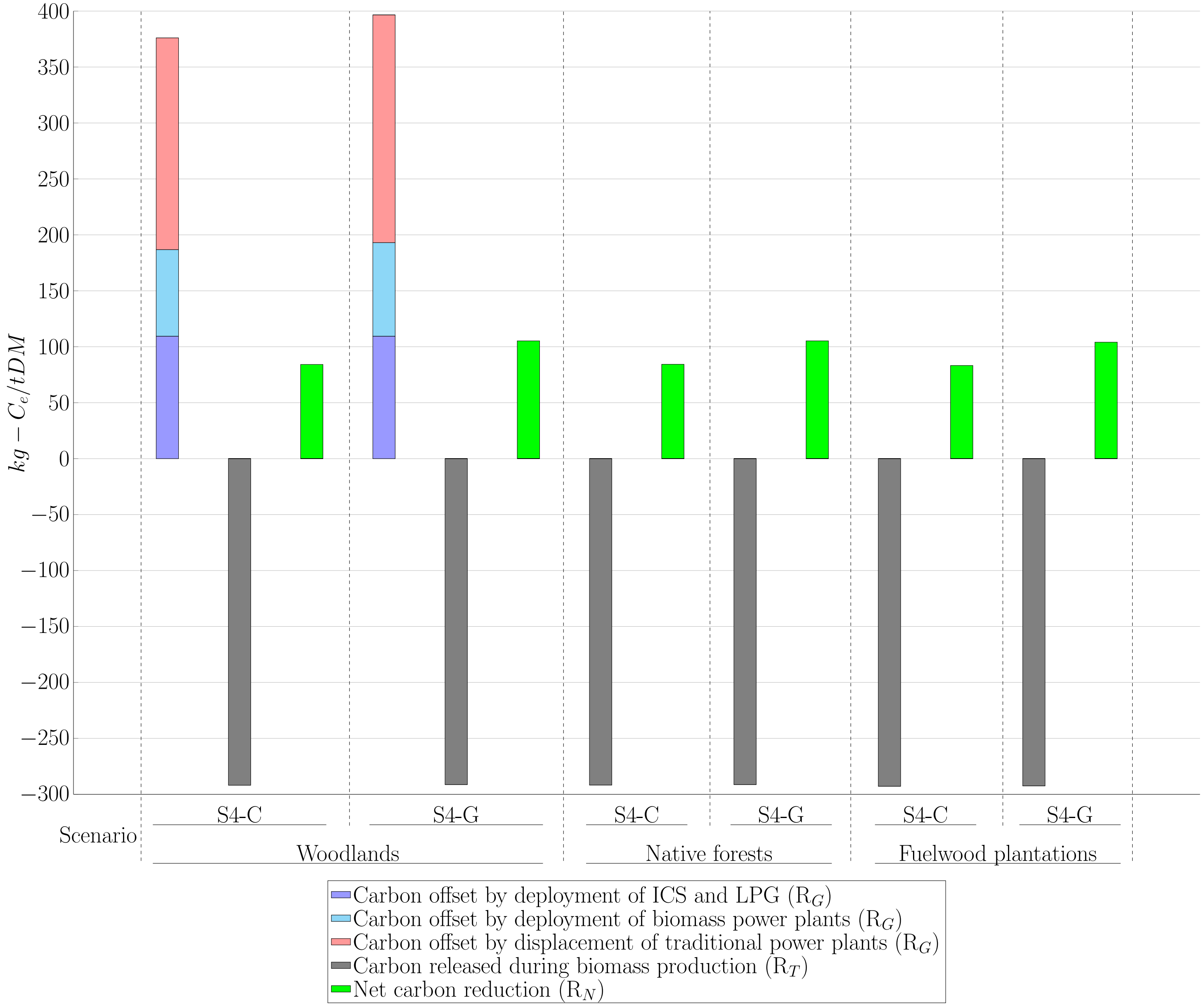


Figure 6: Net reduction in CO_{2e} emissions (R_N, green bars) by deployment of ICSs, LPG stoves and dedicated biomass power plants. Stacking scenario. Note: R_G is defined as the gross CO_{2e} reduction per tonne of dry biomass. R_T refers to the CO_{2e} released by the production of biomass and use of LPG as cooking fuel (grey bars).

Figure 7: Net reduction in CO_{2e} emissions (R_N, green bars) by deployment of ICSs, LPG stoves and biomass CHP plants (scenario 1, 2 and 3). Note: R_G is defined as the gross CO_{2e} reduction per tonne of dry biomass. R_T refers to the CO_{2e} released by the production of biomass (grey bars) and use of LPG as cooking fuel (scenario 2 and 3). The green bars with red border indicate that there is no net reduction in CO_2 emissions, the system is emitting CO_2 to the atmosphere.

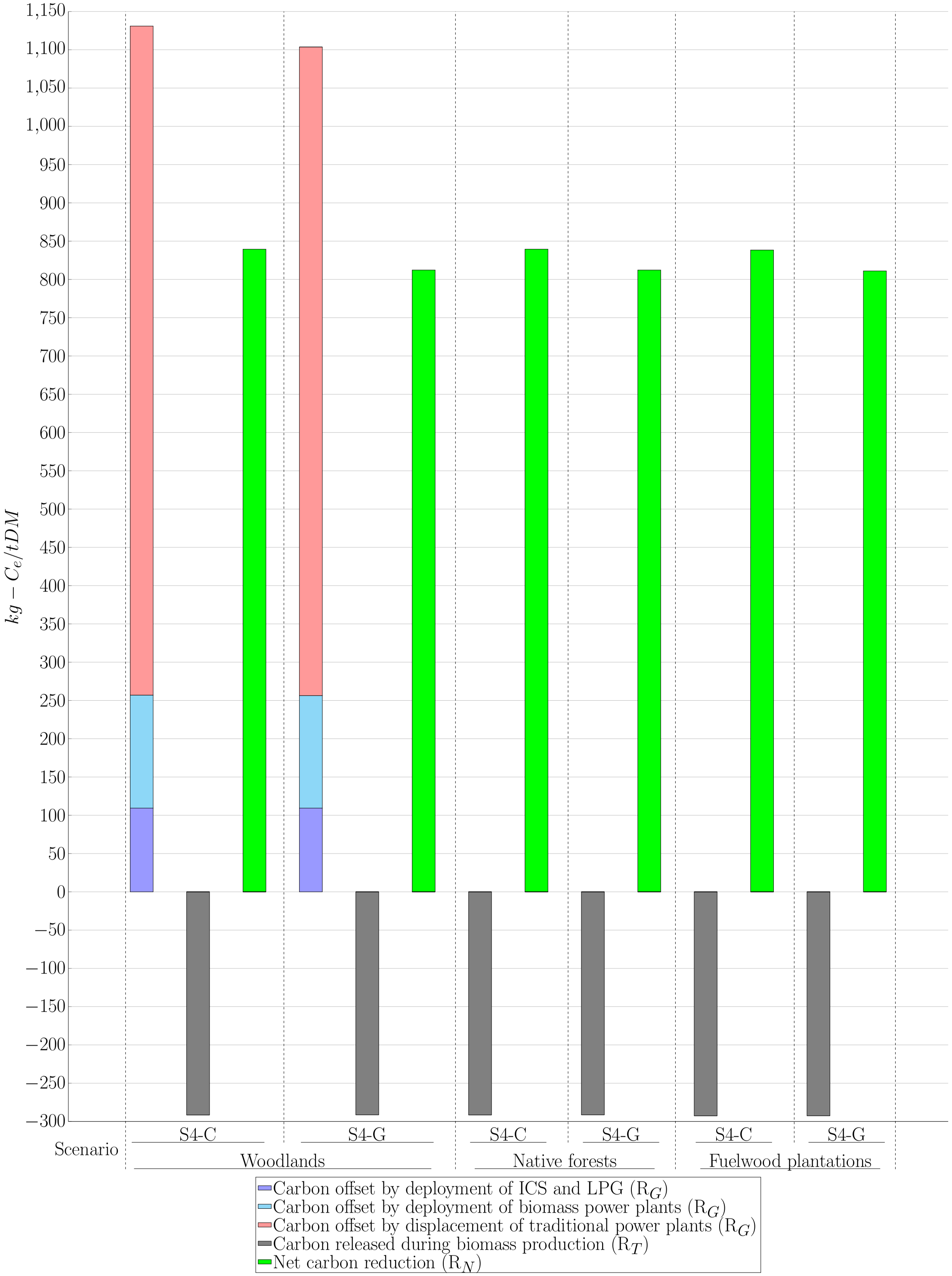


Figure 8: Net reduction in CO_{2e} emissions (R_N, green bars) by deployment of ICSs, LPG stoves and dedicated biomass CHP plants. Stacking scenario. Note: R_G is defined as the gross CO_{2e} reduction per tonne of dry biomass. R_T refers to the CO_{2e} released by the production of biomass and use of LPG as cooking fuel (grey bars).

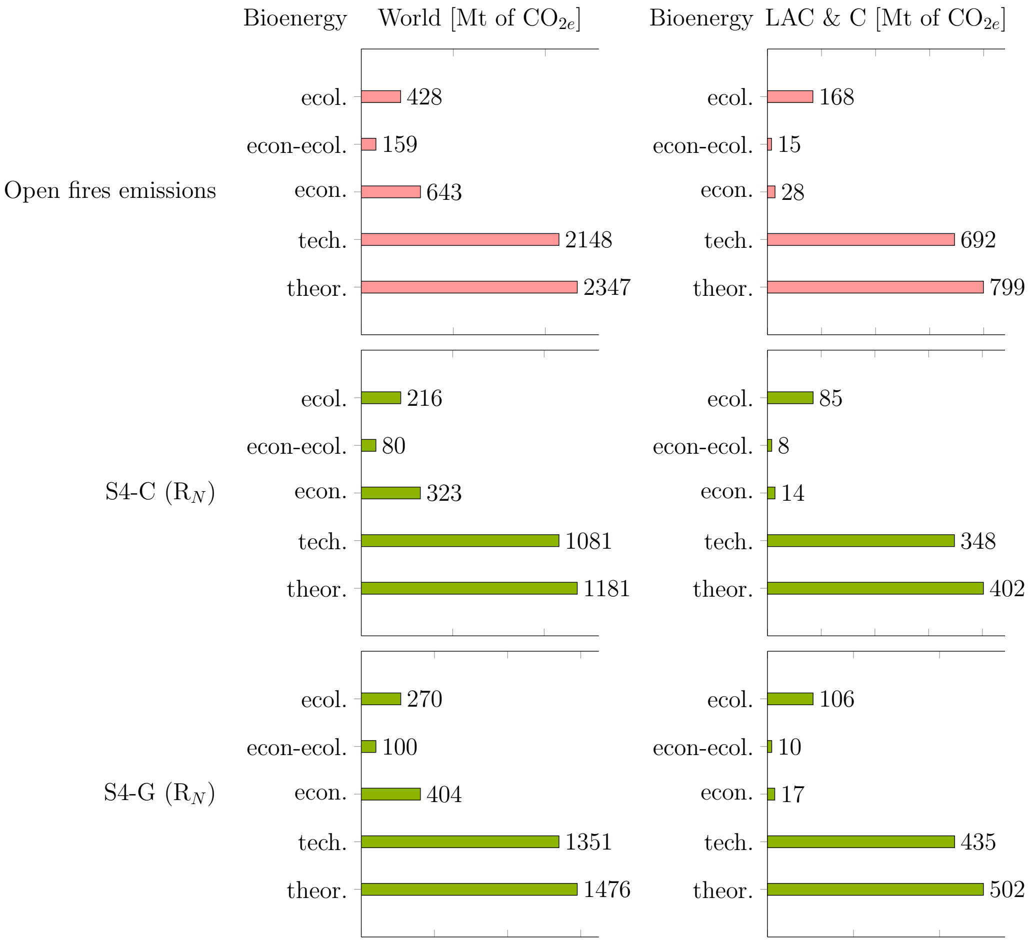
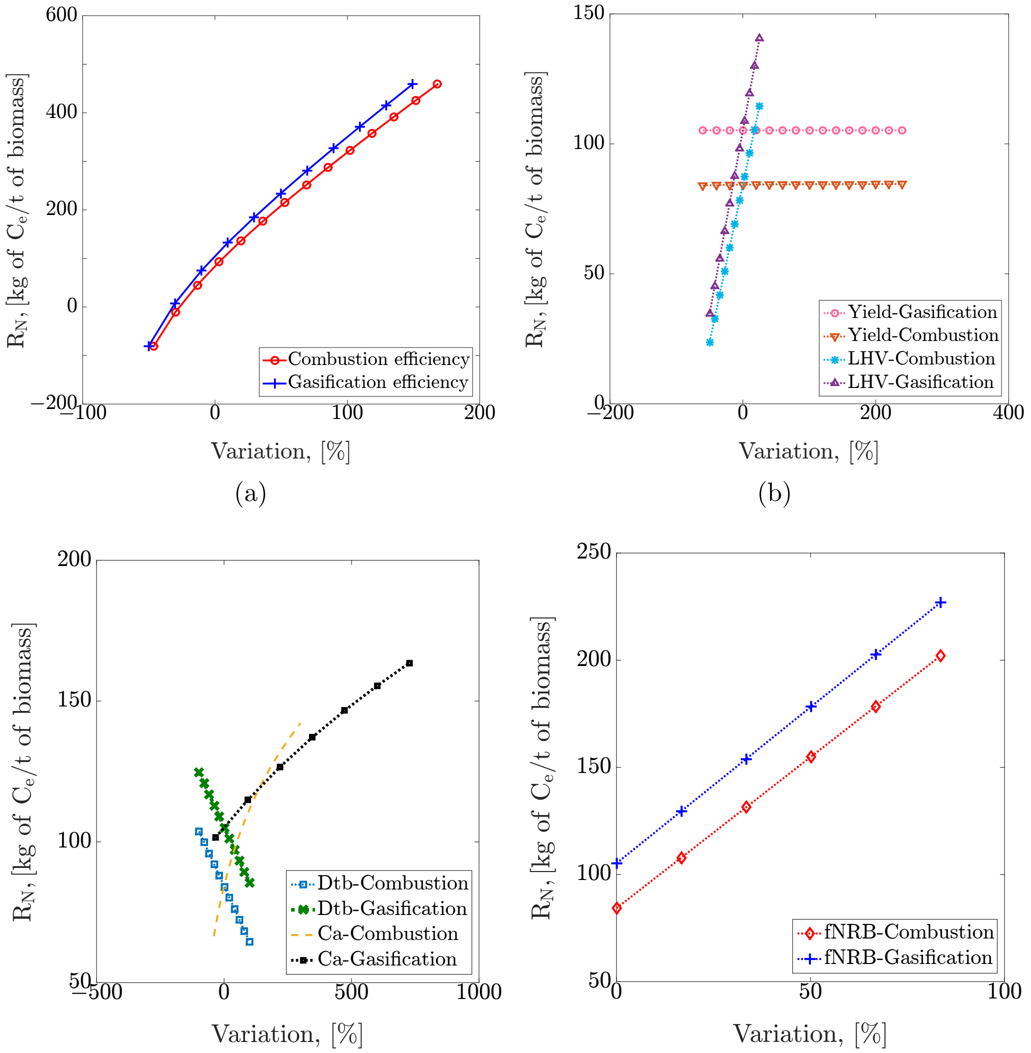


Figure 9: Projected reduction in CO_2 emissions through 2050 from the switch to traditional to modern biomass. Red bars: potential global CO_2 emissions from open fires. Green bars: net reduction in CO_{2e} emissions by using combustion and gasification technologies for 2050.



(a) (b)

(c) (d)

Figure 10: Sensitivity analysis for the net reduction of CO_{2e} emissions using ICSs, LPG stoves and dedicated biomass power plants. This figure was built for scenario 4 conditions. Sensitivity analysis is based on the electrical efficiency of the power plants. The efficiency of the ICSs remained fixed for this analysis.

List of Tables

Table 1: Parameters used for estimating R_P[a]

	Units	Woodlands	Native forests	Fuelwood plantations
Y	t/ha/y	2.5	3.6	5.1
S	y	35	35	15
R_e	kg-C_e/tDM	0	0	1
R_h	kg-C_e/tDM	4	4	4

[a] CSRIO (2003).

Table 2: Parameters used for estimating R_{CB}, R_{TB}, R_T and R_G

	Units	Fuelwood	Ref
C_A	MW	Combustion: 10 Gasification: 0.3	
Y	t/ha/y	See Table 1	
S	y	See Table 1	
L_{CB}	tDM	8	[a]
H_B	GJ/tDM	16	
R_o	km	0.5	[a]
C_{CB}	kg-C_e/tDM/km	0.1	[a]
D_{TB}	km	50	[b]
C_{TB}	kg-C_e/tDM/km	0.4	
R_P	kg-C_e/tDM	See Table 1	
R_{PT}	kg-C_e/tDM	7	[a]

[a] Dote et al. (2008).

[b] CSRIO (2003).