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GLOBAL BIOMASS ENERGY POTENTIAL

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Abstract. The intensive use of renewable energy is one of the options to stabilize CO_2 atmospheric concentration at levels of 350 to 550 ppm. A recent evaluation of the global potential of primary renewable energy carried out by Intergovernmental Panel on Climate Change (IPCC) sets a value of at least 2800 EJ/yr, which is more than the most energy-intensive SRES scenario forecast for the world energy requirement up to the year 2100. Nevertheless, what is really important to quantify is the amount of final energy since the use of renewable sources may involve conversion efficiencies, from primary to final energy, different from the ones of conventional energy sources. In reality, IPCC does not provide a complete account of the final energy from renewables, but the text claims that using several available options to mitigate climate change, and renewables is only one of them, it is possible to stabilize atmospheric carbon dioxide (CO_2) concentration at a low level. In this paper, we evaluate in detail biomass primary and final energy using sugarcane crop as a proxy, since it is one of the highest energy density forms of biomass, and through afforestation/reforestation using a model presented in IPCC Second Assessment Report (SAR). The conclusion is that the primary-energy potential for biomass has been under-evaluated by many authors and by IPCC, and this under-evaluation is even larger for final energy since sugarcane allows co-production of electricity and liquid fuel. Regarding forests we reproduce IPCC results for primary energy and calculate final energy. Sugarcane is a tropical crop and cannot be grown in all the land area forecasted for biomass energy plantation in the IPCC/TAR evaluation (i.e. 1280 Mha). Nevertheless, there are large expanses of unexploited land, mainly in Latin America and Africa that are subject to warm weather and convenient rainfall. With the use of 143 Mha of these lands it is possible to produce 164 EJ/yr (1147 GJ/ha yr or 3.6 W/m^2 on average) of primary energy and 90 EJ/yr of final energy in the form of liquid fuel (alcohol) and electricity, using agricultural productivities near the best ones already achievable and biomass gasification technology. More remarkable is that these results can be obtained with the operation of 4,000 production units with unitary capacity similar to the largest currently in operation. These units should be spread over the tropical land area yielding a plantation density similar to the one presently observed in the state of São Paulo, Brazil, where alcohol and electricity have been commercialized in a cost-effective way for several years. Such an amount of final energy would be sufficiently large to fulfill all the expected global increase in oil demand, as well as in electricity consumption by 2030, assuming the energy demand of such sources continues to grow at the same pace observed over the last two decades. When sugarcane crops are combined with afforestation/reforestation it is possible to show that carbon emissions decline for some IPCC SRES scenarios by 2030, 2040 and 2050. Such energy alternatives significantly reduce CO_2 emissions by displacing fossil fuels and promote sustainable development through the creation of millions of direct and indirect jobs. Also, it opens an opportunity for negative CO_2 emissions when coupled with carbon dioxide capture and storage.

Keywords: biomass, mitigation, carbon dioxide, intensive culture

1. Introduction

Several studies are available trying to quantify global biomass potential. Most of them focus on the use of land but, at least one of them considers biomass stored in the ocean (Hall and Rao 1999). According to Hall and Rao, theoretical biomass resources are potentially the world's largest sustainable energy source comprising about 220 billion oven dry tonne (odt) (or 4,500 EJ) of annual primary production if the marine phytoplankton resource is included. Since this paper evaluates the technical and economical potentials, it is useful to focus on the terrestrial biomass potential, since no quantified cost analysis is yet available for the exploitation of ocean-grown biomass.

The Intergovernmental Panel on Climate Change (IPCC 2001) published an evaluation of the global potential of several alternative energy sources using as constraints land availability. A very useful study on global land availability by Bot et al. (2000) presents a review of some earlier evaluations (Alexandratos 1995; FAO annual; FAO, ongoing; WRI biannual; Wood et al. 1998) and attempts to quantify land availability in almost all countries (160 countries). The study starts from total land area and quantifies the amount of land unsuitable for agriculture due to severe land constraints (hydromorphy: poor soil drainage; low cation exchange capacity: low capacity to retain added nutrients; aluminum toxicity: strong acidity; high phosphorus fixation: a high level of ferric oxides in the clay fraction; vertic properties: dark, expanding and contracting ("cracking") clays; salinity and sodicity: presence of free soluble salts; shallowness: rock or rock-like horizon close to the soil surface; and erosion hazard (a high risk of soil erosion, caused by steep or moderate slopes). In the next step the study accounts for shortage of rainfall and the presence of steep slopes, both effects making land unavailable for agricultural practices (though not for forestry). Next, land availability is analyzed and discounted due to natural or human-induced degradation. The land extension obtained is listed as gross potential arable land for rainfed cultivation. From such value the amount of protected land (which is assumed as a fixed value for the future) and areas used by human settlements are subtracted, yielding net potential arable land. This 'net' land area is then categorized by its capacity to be used for agricultural activities. In the study, the types of land use are accounted for by taking as the basis for evaluation 21 major world crops grown under rainfed conditions and at three different technology levels. Crops yield were compared with observed climatic and soil characteristics. Estimates were made, at country level, of the suitability of land for rainfed crop production, for each crop and at each level of technology, divided into five classes: very suitable (VS), suitable (S), moderately suitable (MS), marginal (M), and not suitable (NS). Land with rainfed crop production potential was taken as land classified as very suitable to marginal (VS, S, MS, or M) for any one of the 21 crops, at the optimum technology level. Based on this criterion it is possible to attribute a weighting factor for these different land qualities that ranges from 0.3 to 1 and add all these weighted areas to obtain the potential equivalent land for rainfed agriculture. The possibility of using irrigation is not considered since the study is mainly concerned with the use of land for biomass energy production that requires low cost of production. According to Table I global net potential arable land area for rainfed cultivation is 3.82 Gha, from which 1.46 Gha were already being used in 1994. Equivalent Potential Arable Land, according to the criteria of the study, is 2.95 Gha.

The IPCC (2001) study considers the total potential crop land to be 2.49 Gha from which 0.90 Gha was already in use for food production in 1990, and assumes that an additional area of 0.42 Gha will be required to feed human population by the year 2050 (assumed as the year of peak global population) yielding 1.28 Gha of land for extra biomass production (by 2050), which could be used for energy provision. Also, based on such land extent and considering:

1. that forests will be the selected form of biomass to be grown in most of these lands;
2. a productivity of forests of 15 oven dry tonnes per ha per year (odt/ha.yr); and, a primary energy content of 20 GJ/odt forest biomass.

It concludes that as much as 396EJ/yr could be produced. An additional 45 EJ/yr is considered available with the argument that this is the present rate of biomass energy consumption, mainly through traditional uses. Thus, the global primary energy potential is 441 EJ/yr.

Other sources of information include IPCC SRES, 2001, from which several papers were assessed in order to estimate GHG emissions scenarios. The results are shown in Table II. It is possible to notice values ranging from 38–660 EJ/yr for 2050 and from 46–1118 EJ/yr for 2100. The highest figures are for energy crops.

Another source of information is presented in a recent IEA study (Fulton and Howes 2004) and synthesized in Table III. There it is possible to notice values up to around 1,000 EJ/yr.

This large range in values quoted in Tables II and III and in the above-mentioned literature demonstrates high uncertainty on the potential of the future biomass energy resource. The higher estimates are mainly justified by the extraordinary potential increase in production that is technically possible. However, attaining such high productivities is in direct conflict with the modest financial support available to foster biomass energy supply and use. Indeed, there are quite modest sources of R&D funds for biomass energy (Criqui et al. 2000) and only one significant large company is presently involved in the activity (Arthur, Daniels and Midland in USA). Also, biomass energy is traditionally used in developing countries and only in the last 15 years has there been any new significant interest for its wide use in a few developed countries (e.g., Sweden, Austria, Finland, USA).

When analyzing technical-potential evaluations of global primary biomass energy it is important to note that some of them assume that forests will be the major source of biomass. This may be a good assumption for temperate countries but not necessarily for tropical and sub-tropical countries. The possibility of using biomass energy crops on a large-scale has been investigated for some time (IPCC

TABLE I

Comparison of actual and potential available arable land for rainfed agriculture

	Gross potential arable land (rainfed cultivation) (1,000 ha)	Protected land		Settlement (% of total area)	Net potential arable land (rainfed cultivation) (1,000 ha)	Actual arable land (1994) (1,000 ha)	% of potential arable land (rainfed cultivation) actually in in use (1994)	Equivalent potential arable land (1,000 ha)
		% of total area	% of potential arable					
Sub-Saharan Africa	1,119,492	8.6	4.3	1.9	1,050,083	157,608	15	752,344
North Africa and Near East	50,017	8.1	4.0	6.4	44,815	71,580	160	29,009
North Asia, East of Urals	286,800	3.0	1.5	(2.3)	275,802	175,540	64	226,774
Asia and the Pacific	812,561	9.4	4.7	3.9	742,672	477,706	64	561,890
South and Central America	1,046,071	10.6	5.3	1.2	979,946	143,352	15	743,243
North America	463,966	9.9	4.9	(2.1)	431,465	233,276	54	345,169
Europe	363,120	10.1	5.0	(5.8)	323,803	204,322	63	286,887
World	4,144,017	8.9	4.4	2.8	3,818,809	1,463,384	38	2,945,316

Notes. *Protected Land* Data from Green and Paine (1997) for the proportion on potential arable land. *Settlement Developing regions* from Alexandratos (1995); taking forecast populations for 2010. Percentages shown as ( ) are based on 33 ha per 1000 population. *Equivalent potential arable land* – Data from Bot et al. (2000).

TABLE II
Estimates from the literature on the global potential of biomass energy

		Biomass residue potentially available (EJ/yr)			
		Year			
Source[a]	Types of residues[b]	1990	2020–2030	2050	2100
1	FR, CR, AR		31		
2[c]	FR, CR, AR, MSW		30	38	46
3	FR, MSW		90		
4					272
5	FR, CR, AR, MSW			217–245	
6		88			
7[c]	FC, CR, AR, MSW		62	78	
8	FR, CR, AR		87		
A1[d]	Energy crops			660	1118
A2[d]	Energy crops			310	396
B1[d]	Energy crops			449	703
B2[d]	Energy crops			324	485
9	Energy crops, FR, CR			273–1381	

Source. Johansson et al. (2004).
[a]1:(Hall et al. 1993, 2: Williams 1995, 3: Dessus et al. 1992, 4: Yamamoto et al. 1999, 5: Fischer and Schrattenholzer 2001, 6: Fujino et al. 1999, 7: Johansson et al. 1993, 8: Swisher and Wilson 1993 9: Smeets et al. 2004.
[b]FR: forest residues, CR: crop residues, AR: animal residues, MSW: municipal solid waste.
[c]These studies rather estimated the potential contribution, instead of the potential available.
[d]IPCC 2000.

1996; Johansson et al. 1993) and can represent a significant share of the biomass commercially produced (see Tables II and III). The energy crops option is driven by the higher productivity and the shorter time elapsed between plantation and harvest compared with forest, as shown in Figure 1. It is quite interesting that the best records are for: (1) irrigated sugarcane grown on 10,000ha field in Zambia achieving 1,350 GJ/ha.yr[1]; (2) sugarcane global average 650 GJ/ha/yr; (3) the best Eucalyptus plantation by Aracruz in Brazil with 1000 GJ/ha yr; and (4) average plantation in Aracruz, Brazil of 450 G/ha yr. These figures should be compared with wood from commercial forests in USA which currently achieve less than 100 GJ/ha yr and Alamo Switchgrass in USA 430 GJ/ha/yr. Results show that tropical countries present high productivity, and biomass crops grown in suitable soils make better use of land to produce energy.

Nevertheless, in this study we also consider carbon (C) storage and abatement from forest plantation. In temperate and boreal areas this option is probably the best alternative for biomass contribution on carbon mitigation, and in tropical areas

TABLE III

Estimates of long-term world biomass and liquid biofuels production potential

Author(s)	Study publication date	Time Frame of estimates (and low/high for ranges)	Type of estimates (technical or economic potential, feedstock types included)	Raw biomass energy potential (exajoules per year): Crops (grains, sugars, cellulose)	Biomass waste (agricultural, forest, other)	Total	Liquid biofuels energy potential after conversion (exajoules per year)[a]	Notes
IPCC Third Assessment Report: Mitigation	2001	2050	Technical	440	N/A	440	154	Declines due to increasing food requirements
		2100	Technical	310		310	109	
Fischer and Schrattenholzer (IIASA)	2001	2050, Low	Technical	240	130	370	130	Economic estimate for 2050 assumes continued technology improvements, cost reductions to ethanol
		2050, High	Technical	320	130	450	158	
		2050	Economic	A/NR	A/NR	150	53	
Yamamoto et al.	2001	2050	"Practical" (lower than technical)	110	72	182	64	Assumes declining land availability due to population pressure pressure
		2100		22	114	136	48	
Moreira	2002	2100	Technical (crop waste included in total estimate)	1301	N/A	1301	455	Emphasizes high efficiencies from coproduction of liquid biofuels and electricity
Lightfoot and Greene	2002	2100	Technical (just energy crops)	268	N/A	268	94	Looks only at dedicated energy crops, not food crops
Hoogwijk et al.	2003	2050, Low	Technical	0	33	33	12	Wide range of input assumptions used
		2050, High	Technical	1054	76	1130	396	

Source. Fulton and Howes (2004).

[a]Estimates with (a) were made by IEA, based on converting author's biomass energy estimate to liquid fuels at a 35% energy conversion rate, similar to rate assumed by Moreira, Lightfoot and Greene and others when co-generating with electricity, and assuming a slight improvement for 2050. Note that none of the liquid biofuels potential estimates account for the possibility that some biomass may be used for traditional purposes, which could "divert" up to 50 exajoules.

A/NR: assessed but not reported; N/A: not assessed.

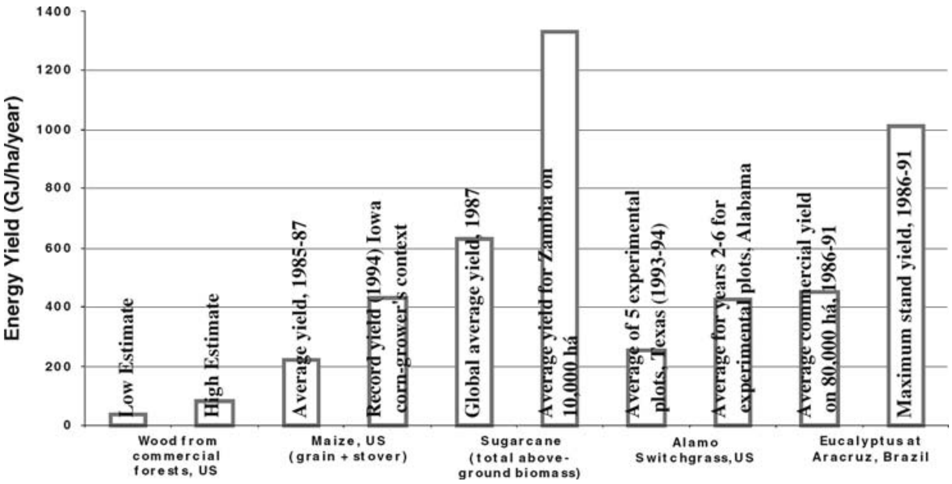

Figure 1. Actual biomass energy yields from various activities. (Source: IPCC 1996)

there are large extents of land inappropriate for agricultural activities. Total carbon mitigation from planted forest is accounted through the use of one selected scenario discussed in the Second Assessment Report of IPCC (IPCC 1996)

2. Bioenergy from Sugar Crops

Based on the above discussion an investigation of the potential of some biomass crops has been carried out, since forests have been more intensively accounted for in the literature. Energy crops look more suitable for tropical countries (sugarcane is probably the most interesting one, while oil palm also deserves attention[2]) and in sub-tropical countries (sweet sorghum is considered as a good candidate).

Figure 2 displays the present amount of land being used for the major crops at world level. Also, their distribution on some land-rich countries is shown. It is interesting to observe that the major crops occupy 230 Mha (wheat), 180 Mha (rice), and 160 Mha (maize) globally. Also, it is noticeable that rice monoculture in India exceeds 40 Mha, while soybeans in USA exceeds 30 Mha. On the other hand sugarcane, at global level, uses a little more than 20 Mha (FAO Database).

Figure 3 shows the amount of biomass harvested. It is important to notice that sugarcane is the second largest contributor, just after all cereals added together. If sugarcane tops and leaves (usually known as 'barbojo'), that are often burned before harvest, were also collected, the 21 Mha of sugarcane planted could produce 1750 Mt/yr of biomass, compared with 2400 Mt/yr of biomass from all cereals which cover more than 700 Mha of land.

Figure 4 shows the energy content of selected biomass residues for some land-rich countries and for the world. As noted, all cereals accumulate 42 EJ/yr,[3] while

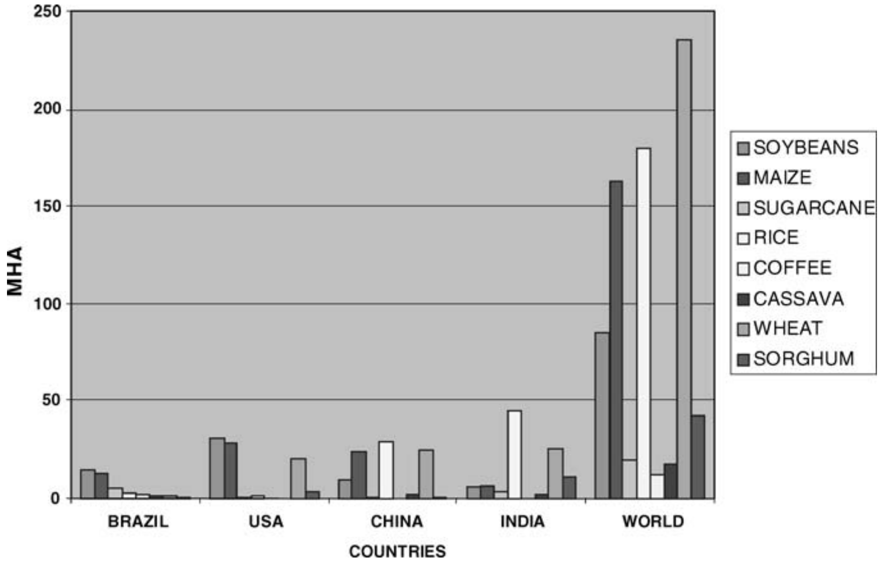

Figure 2. Harvested areas for some major crops – 2001. (Source: FAO Database)

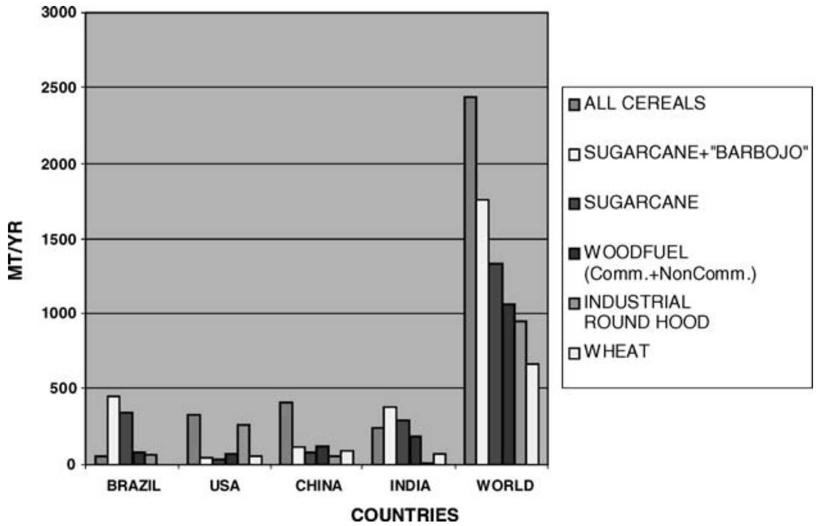

Figure 3. Amount of biomass harvested-major categories – 2001. (Source: FAO Database complemented by author)

sugarcane (solid biomass plus the fermentable juice) represents only 13.5 EJ/yr. Nevertheless, if all sugarcane planted areas had yields similar to the best sugarcane yield, this value would be increased to 24 EJ/yr. Such figure is still below the value for all cereals and all wood (wood fuel plus industrial round wood), but it

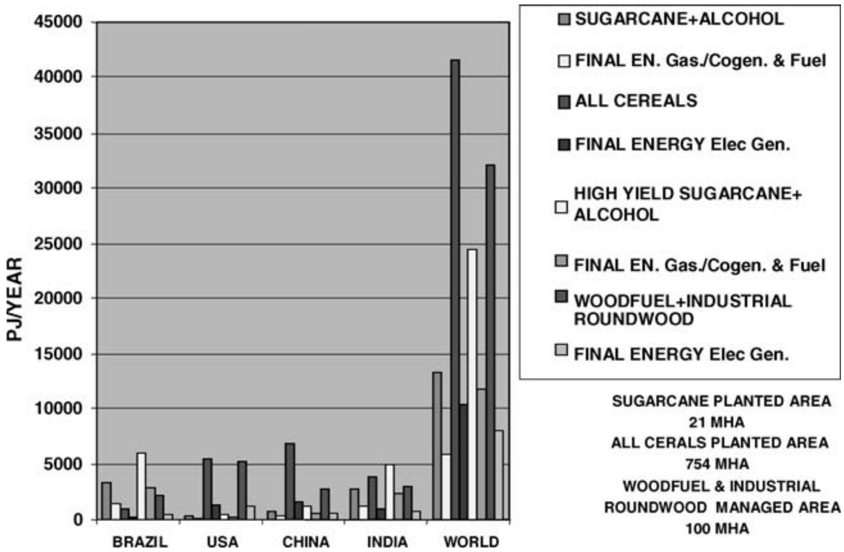

Figure 4. Energy content in some biomass residues – World 2002. (Source: FAO Database complemented by the author)

is important to note the significant difference in planted land areas (21 Mha for sugarcane, 754 Mha for cereals and 100 Mha for forests).

3. Future Scenario for Energy from Sugarcane – A View from Brazil

As already discussed, the highest productivity of biomass is found in tropical countries and this is directly associated with obtainable primary energy yields. However, for satisfying human needs what is really important is the final energy quantity that can be produced from biomass and delivered as energy services. This is a key issue not considered in any IPCC evaluations, since we cannot take for granted that all sources of biomass will be converted to the final energy carrier with the same efficiency as available for conventional sources.

Figure 5 shows the final energy produced from the more relevant forests and crops. For forests (including tropical) genetic improvement, better fertilization and even irrigation (which may not be sustainable due to global water limitations) are considered. Sugarcane can yield in the near term 260 GJ/ha yr, while the most efficient tropical forests may yield around 135 GJ/ha.yr, when starting from 450 GJ/ha yr of primary energy.[4] In the long term sugarcane can provide up to 400 GJ/ha yr, while tropical forests may reach 300 GJ/ha yr. The major drivers for long-term yields from sugarcane are the use of all above-ground biomass (bagasse, juice and barbojo) that can be sustainably harvested, as well as species improvement and dissemination of the best varieties and practices to all plantation sites. In order to obtain 390 GJ/ha yr of final energy from 860 GJ/ha yr of primary energy

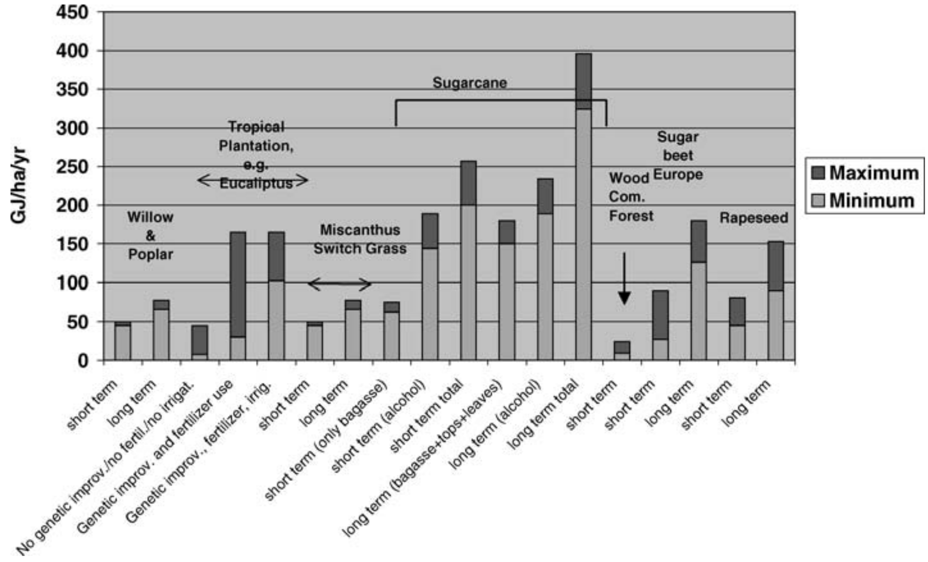

Figure 5. Final energy produced from crops and plantations. (Source: Author)

(all above ground biomass average yield by 2020–30) the following assumptions are made:

1. 40% of the barbojo is left on the ground to protect the soil
2. all remaining solid biomass primary energy will be converted to final energy through cogeneration plants.

This last assumption is quite feasible since today most sugar mills produce their entire steam requirement, as well as their electricity needs through the use of cogeneration facilities. It is quite important to observe that the overall conversion efficiency for ethanol and electricity production may approach 55%, which is a high value (Moreira 2002). The use of biomass from forests is usually limited to the exclusive production of electricity when evaluating large energy supply programs. This happens because biomass transportation adds significantly to the cost of energy produced, therefore requiring transformation from primary to final energy forms to be carried out close to the resource base. Consequently, the opportunity to use steam in nearby industries is limited, while electricity can be transported for long distances through the grid. Thus, since only electricity demand exists, the conversion efficiency from primary to final energy is limited to figures around 40%, even using gasifiers and combined cycle power plants (Williams and Larson 1993).

The validation of the potential use of sugarcane as a significant source of energy may be obtained by examining the evolution of its market in Brazil. Sugarcane harvesting in Brazil has been reaching the level of 300 Mtonnes/yr since 1998 and in 2004 should exceed 350 Mtonnes. Ethanol production peaked in 1998 to almost 15 million m^3 and declined since then until 2001 due to the lack of interest from consumers in the acquisition of new neat ethanol cars. This loss of consumer confidence was a consequence of the uncertainty regarding reliable supply of the product triggered by the ethanol shortage that occurred in the early 1990s. Nevertheless, the use of a blend of 24–26% ethanol in all gasoline, which is supported by legislation, was able to minimize alcohol market losses. By 2002, the significant price differential between ethanol and gasoline/ethanol blend in service stations renewed the interest of consumers and the sales of neat ethanol vehicles increased once more reaching the modest level of 3%, much better, however, than figures like 0.1% which occurred during the period 1999–2001. A big boom in ethanol consumption has take place since 2003 due to the introduction of the fully flexfuel vehicle (FFV) by some automobile manufacturers (Fiat, GM, and Volkswagen). Such cars can use ethanol in a range of blends varying from 0% up to 100%. This is a much more flexible range than the one valid for flexfuel vehicles in the USA, although it should be remembered that all gasoline in Brazil contains 24–26% of ethanol by volume.

The success of flexible-fuel vehicle became very apparent during 2004, and it is expected that around 20% of all new car sales will have been supplied with this technology by the end of the year. The reasons for such high acceptance from consumers is the increase in reliability of fuel supply, the possibility of reducing operational cost by choosing the least expensive alternative each time a refill is performed,[5] and the price of vehicles which does not differ from the gasoline or neat ethanol version.

Another important aspect of this biomass source is the significant potential to generate surplus electricity by using the sugarcane by-product bagasse and improving boiler efficiencies. This alternative has been well known for a long time, but only after 1997, with the implementation of new energy policies allowing the operation of Independent Power Producers, has commercialization of electricity become a frequent option in sugarcane mills. Figure 6 shows that within 7 years (1997–2004) the amount of electricity sold to the grid increased from 80 to 1320 GWh annually. This increase was essentially carried out by retrofitting existing energy supply facilities in some 30 sugar mills (from a total of 303 presently in operation in Brazil). A continuous expansion of electricity supplied from sugarcane is expected as a consequence of a new program that has recently been created by the Federal Government (PROINFA). PROINFA guarantees a supply of up to 1100 MWe from biomass sources up to 2006 through Power Purchase Agreements. The program will be further expanded after 2006, up to the limit of 10% of the total installed capacity (around 9,000 MWe, from which one third will be from biomass electricity generation, one third from wind and one third from small hydro).

PROINFA is a voluntary electricity sale program for some new and renewable energy sources (biomass, wind and small hydro) designed to foster their use through acquisition of electricity by consumers at a subsidized price. Nevertheless, the price offered for sugarcane-based electricity generation is the lowest of all new and renewable alternatives and at the same level as electricity being acquired from new hydroelectric plants (US$30/MWh) while wind energy is quoted at US$60–70/MWh.

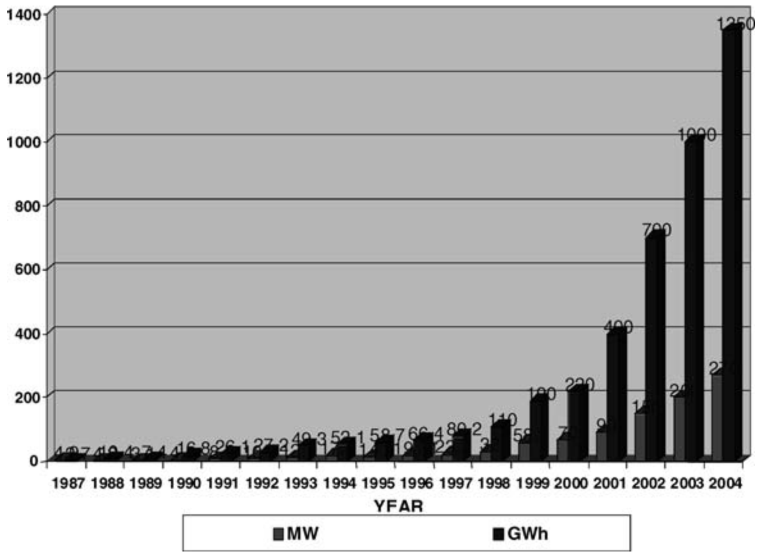

Figure 6. Evolution of cogeneration in sugar mills-electricicity sold to the grid state of São Paulo. (Source: CPFL 2003)

All the electricity being produced from sugarcane, as well as the projects being implemented under PROINFA, that are to become operational by 2006, use steam turbines (partial extraction steam turbines for ethanol and/or sugar processing, and also condensing steam turbines) fed exclusively by bagasse. This technology allows the generation of 100 kWh/tonne of sugarcane (Moreira 2002). With the use of barbojo on top of bagasse, steam turbines may produce 280 kWh while biomass gasification together with steam-injected gas turbines may yield near 700 kWh/tonne. Thus, with a sugarcane production of 400Mtonnes (a figure similar to the yield achieved in 2004) as much as 280 TWh/yr could be generated – an amount near the present total electricity production in Brazil (350 TWh/yr). Since it is agreed that some fraction of barbojo should remain in the ground to protect the soil, a more conservative but sustainable generation factor is considered to be near 500 kWhe/tonne (200 TWh/yr).

4. A Future Scenario for Energy from Sugarcane – A Global View

Based on the results described in Section 3 it is possible to construct a plausible scenario for large-scale use of sugarcane for energy production. Scenario's assumptions are:

- A global sugarcane plantation effort will be conducted in the period 2003/2030.
- The total planted area for sugarcane crops in several countries will reach 143 Mha by 2030.

TABLE IV

Amount of energy produced from sugar/alcohol mills distributed over world agricultural land area at a density of 1 every 6,200 km^2 – BIG, Combined Cycle, and 40% more yield – total number of renewable energy producing units is 4,000

Final energy category	Primary energy (EJ/yr)	Final energy (EJ/yr)	Total land area used for crops
Electricity	94.1	37.9	
Liquid fuel	69.9	51.5	
Total	163.9	89.5	1.43×10^6 km^2

Source: Author.

- Improvement in agricultural practices will allow a yield of 140 t/ha/yr of sugarcane at the end of the period (by 2027).

In order for the above assumptions to be achieved, an annual increase in sugarcane planted area of just less than 8% is necessary. Also, annual sugarcane yield improvement of 3%[6] and an increased electricity production efficiency from today's average in Brazil of 30 kWh to 500 kWh/tonne of cane are needed. Finally, an increase in sugar content to allow ethanol production to rise from the present best practice level of 90 liters to 114 liters/t cane by 2030 is required. These goals can only be achieved with the development of policies in several tropical countries capable of motivating farmers, similar to the ones used in Brazil at the beginning of the ethanol program (e.g. temporary subsidies, low interest loans, incentives to ethanol based vehicles) and others still in use today like a minimum guarantee level of ethanol use, temporary subsidies for electricity generation, as well as some practices not yet implemented such as significant financial support for research and development. In particular, a yield increase of 3% per year has to rely strongly on R&D, since the average evolution in the last two decades was only around 0.7%/yr as opposed to annual yield improvements of 1.5 to 2% for cereals and sugar beets (FAO Database).

If the scenario goals are achieved, it should be possible to produce 163.9 EJ/yr of primary energy as shown in Table IV. This would require the operation of 4,000 units, each one able to handle 5 Mt of sugarcane per year (25,000 t/day during 200 days). A good parameter to estimate this scenario's feasibility is the implied necessity of constructing one unit every 6,200 km^2, which is the present density of sugar mills (if all had 5 Mt of annual cane crushing capacity) in the state of São Paulo, Brazil where 40 million people live in an area of 270,000 km^2 and which boast the country's highest income.

5. A Role for Forest Biomass

In the global assessments carried out by IPCC (IPCC–SAR, 1996 and IPCC–TAR-Mitigation, 2001) a detailed model was presented with the purpose of analyzing an

TABLE V

Regional estimates of land availability, average mean annual increment (MAI), rotation length, and planting rate for a global forestation program, including establishment of plantations and agroforestry, to sequester C (data from Nilsson and Schopfhauser 1995)

Region/country	Land available[a] (Mha)	MAI (m^3/ha/yr)	Rotation length (yr)	Planting rate[b] (Mha/yr)
High Latitudes				
Canada[c]	28.3	2.5–8.0	60	1.14
Nordic	0.35	5	60	0.014
FSU	66.5	3	80	1.66
Mid-Latitudes				
USA	21.0	6–15	15–40	0.70
Europe	7.74	6–10	20–60	0.31
China	62.5	2.3	80	2.5
Asia	12.5	12	40	0.50
South Africa	1.9	16	30	0.075
South America	4.6	15	25	0.18
Australia	4.3	6–23	30	0.123
New Zealand	5.0	25	25	0.1
Low Latitudes				
Tr. America	40.8	8–25	20	0.74
Tr. Africa	31.6	8–16	30	0.58
Tr. Asia	57.7	8–16	20	1.05

[a]Full details of sources are provided in Nilsson and Schopfhauser (1995); many of the sources originate from individual countries.

[b]Includes rate of establishment of both plantations and agroforestry systems.

[c]Canada includes not satisfactorily restocked (NSR) forest areas in addition to marginal agricultural lands (Van Kooten 1991); the low end of the MAI was used for NSR forests.

extensive program of forest management. According to these references it should be possible to accumulate 60 to 87 GtC during the period 1995–2050 through slowing deforestation over an area of 138 Mha combined with natural forest regeneration over an area of 217 Mha inside the tropics, as well as the implementation of a global afforestation/reforestation program covering an area of 345 Mha. Table V shows the details of the afforestation/reforestation part of the program. Land area is not a constraint for such forest management. Table VI shows the extent of all land available in the world according to the particular category of vegetation. Tropical savannas and temperate grassland, which are the best candidate areas for forest planting, exceed 3,500 Mha.

From our earlier discussion it is clear that many other studies are available with different estimates of land area usage and different intensity of forest activities. For the purpose of carrying out our own evaluation of carbon abatement potential by

TABLE VI
Estimates of vegetation areas (from Bolin et al. 2000; based on WGBU 1998)

Biome	Area (million ha)
Tropical forests	1,760
Temperate forests	1,040
Boreal forests	1,370
Tropical savannas	2,250
Temperate grasslands	1,250
Deserts and semi-deserts	4,550
Tundra	950
Wetlands	350
Croplands	1,600
Total	15,120

forests through the combination of sequestration and renewable energy production displacing fossil fuels we will use this data as our proxy. Also, in order to simplify the evaluation, a single average value for regions where a range of values is available, has been adopted for both the Mean Annual Increment (MAI) and the rotation period, according to Table V.

Based on these figures an overall value of 40 GtC for C stored in forest and forest products has been obtained, in agreement with the range of values described in IPCC (named in this paper as SAR Forest Model). Note that we only consider the 345 Mha of land and assume it would be fully used for afforestation/reforestation. In reality, the data in the IPCC study show contribution from slow deforestation and regeneration in the range of 22.3–49.5 GtC. This means that the contribution of afforestation/reforestation in that study is around 38 GtC (60–29.3 or 87–56.5).

The approach suggested in IPCC has a significant economic barrier, since the afforestation/reforestation program would be mainly performed with the purpose of mitigating carbon emissions. A more realistic approach would be to base the activity on the objective of extracting the wood at the end of the growing season, and then using it for several purposes, while continuously reforesting the harvested areas. Considering the large amount of wood available, all such material, once harvested, will be assumed to be used for energy production.

Since our evaluation contemplates the period 2003–2050, this new assumption only impacts on land use in the USA, part of Europe, South Africa, South America, Australia, and New Zealand among the Mid Latitude countries, and all Low Latitude areas, all with a rotation period of 47 or fewer years (see Table V). With the assumptions that: (i) all harvest wood will be used for electricity generation displacing fossil fuel with similar primary energy to electricity conversion efficiency as these fuels; (ii) harvesting and transportation of wood requires the same amount of energy that is spent for these equivalent operations carried out for fossil fuels[7]), it is possible to calculate the contribution of carbon stored in forests as 23 GtC, while in harvested wood it is 17 GtC, yielding the same total previously found value (40 GtC).

The difference is that the commercial interest in wood for energy production may allow a more optimistic scenario. The approach is to use typical results for eucalyptus plantation in Brazil within all tropical America and Asia where the growing period is 20 years (see Table V). In this case the carbon mitigation from forests increases from 40 to 51 GtC (24 GtC stored in forest and 27 GtC in harvested wood).[8]

Figure 7 displays the amount of C sequestered from the 345 Mha man-made forest as well as the amount of C stored in forest and harvested wood either for the rotation cycle of several decades (as listed in Table V) or for the situation where short harvesting cycle (like the one applied for eucalyptus plantation in Brazil) is considered for tropical America and tropical Asia. It can be noticed that with short cycle harvesting periods, the total C stored is 1.3 times larger. Also, it is important to note that fast growing trees were considered to cover just over 98.5 Mha of the 345 Mha.

It is also possible to couple Carbon Capture and Sequestration (CCS) to the biomass energy production process. Considering the high amount of harvested biomass even in the less optimistic scenario (35 Gt of wood in 47 years) with a total primary energy content of 700 EJ, around 2,500 units, with 200 MW each will have to be operated by the year 2050. By this time these units will be consuming 37 EJ/yr of primary energy while generating 14.8 EJ/yr of electricity.

The economic cost of carbon capture and storage for 200 MWe units is high (Mollersten et al. 2003). Assuming that 80% of the CO_2 emitted could be captured, as much as another 22 GtC could be abated for the most optimistic forest growth

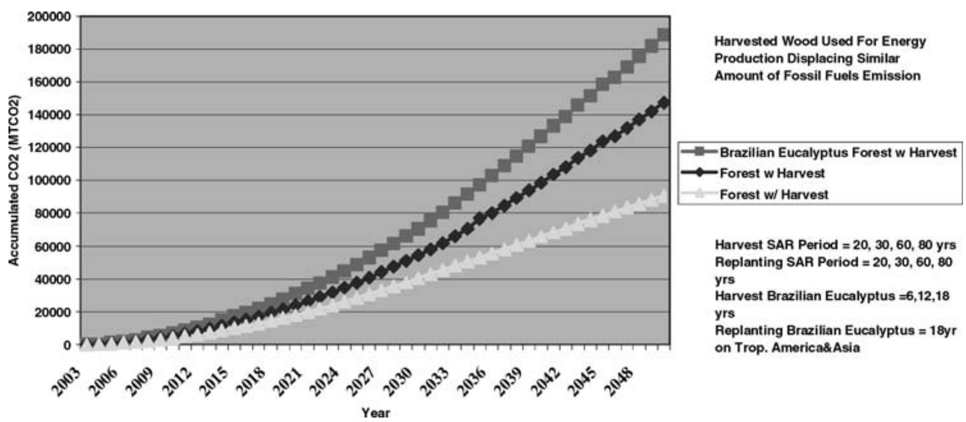

Figure 7. C abatement from SAR forests without harvesting, with harvesting at end of growth season and with harvesting as practiced in Brazilian Eucalyptus for tropical America and tropical Asia areas.

approach (fast-growth trees). Considering the primary energy that would be required for carbon capture and storage, it would be more realistic to consider 16 GtC (or 72.5%) as the extra volume abated from the atmosphere during the period 2003–2050.

6. Impacts on the Global Environment

6.1. Sugarcane plantation

With the production of 38 EJ/yr of electricity and 51.5 EJ/yr of ethanol from sugarcane plantations (see Table IV) it would be possible to abate significant amounts of CO_2 emissions as shown in Figure 8.

This level of liquid-fuel production should be more than enough to cover all the increase in oil demand if it is assumed that future oil consumption will continue to grow at the average rate observed during the period 1980–2000 (see Figure 9). Also, all global electricity demand growth, based on this same business-as-usual scenario, could be supplied by the electricity generated from these 4,000 sugar mills, by the year 2030 (see Figure 10).

6.2. Forest plantation

For the afforestation/reforestation scenario, instead of building a bottom-up perspective based in the amount of biomass energy available for power generation it would be better to analyse the results based in the amount of CO_2 stored in trees, soil and harvested wood. This is more useful since, as opposed to the sugarcane

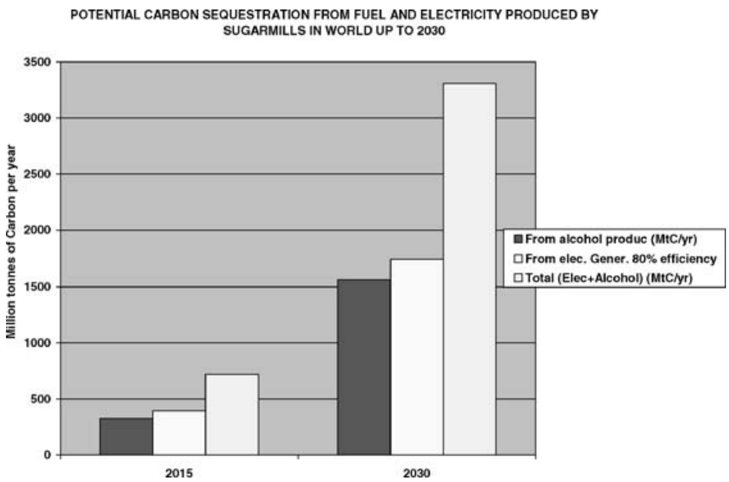

Figure 8. World carbon abatement in 2030 (2015) due use of sugarcane biomass in 143 (45) MHA. (Source: Author)

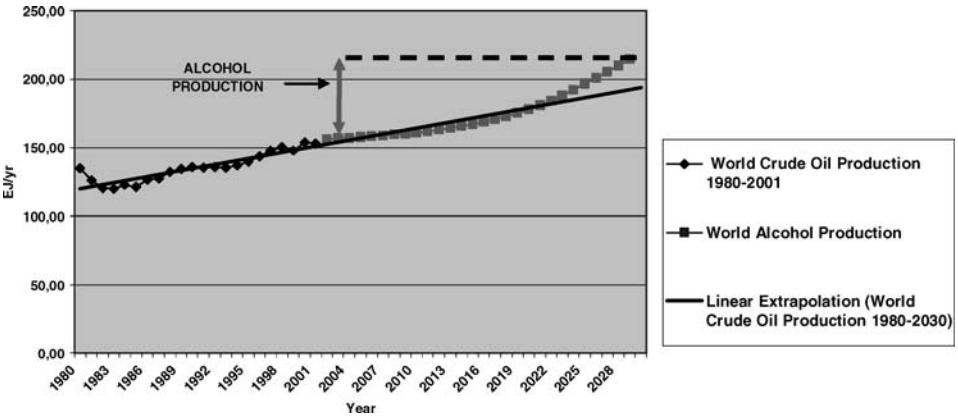

Figure 9. Historical global oil production and future alcohol production from sugarcane – 1980–2030. (Source: Historical data from British Petroleum (BP, 2003) and projection prepared by Author)

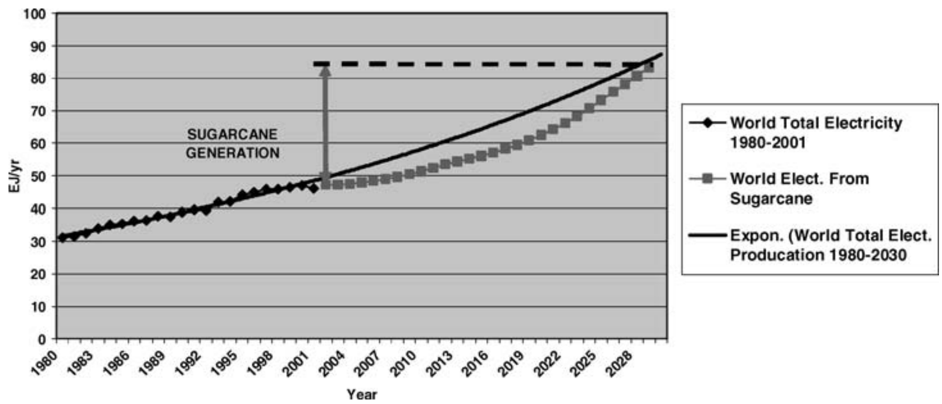

Figure 10. World historical generation plus future generation at histrocial trend and potential sugarcane based generation – 1980–2030. (Source: Historical data from British Petroleum (BP, 2003) and projection prepared by Author)

scenario, a significant amount of C-mitigation will be provided by C stored in forest and in its soils.

A convenient way to analyse the impact on mitigation is to examine some possible emission scenarios with and without the existence of such projects. Since impacts caused by sugarcane crops will also be shown in such emission scenarios we will add them to forest results in order to save space. Figure 11 uses the B1 scenario (IPCC-SRES). Whilst the B1 scenario emissions peak around 2040, sugarcane plantations significantly reduce CO_2 emissions from fuel and land, bringing emissions around 2030–2050 below the level of 1990. There are two curves for sugarcane plantation. The upper one is the new level of global CO_2 emissions if

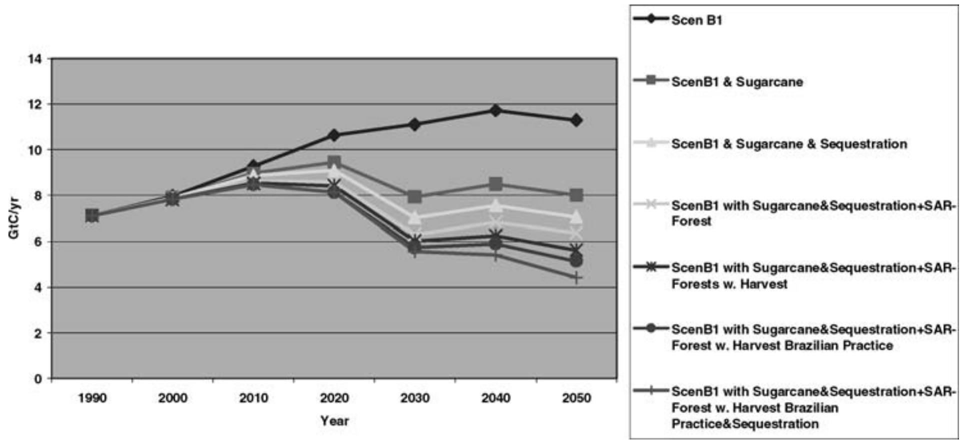

Figure 11. CO_2 energy and land use emissions in scenario IPCC B1, with sugarcane, and with sugarcane plus SAR-Forest. (Source: IPCC 2000 and Author)

alcohol and electricity only were produced and used to replace gasoline and fossil fuels consumed for electricity generation. The lower curve assumes that, on top of alcohol and electricity production, CO_2 is captured and stored. The next four lower curves show global CO_2 emissions when sugarcane plantation is combined with afforestation/reforestation. The upper one assumes that the forest will not be harvested. Next there is a curve with results for forest with long harvesting cycles (as shown in Table V) while the following one assumes, in tropical America and Asia, that fast-growing trees (like eucalyptus) will be planted and harvested. Finally, the last curve assumes that CCS will also occur for electricity production from harvested wood. It is remarkable that by 2050 a level around 4.4 GtC/yr for global CO_2 emissions from energy and land is expected. In reality, assuming the full figure of the SAR-forest model, where forest management would be carried out in 700 Mha, instead of the 345 Mha considered in Section 4, an extra mitigation of 0.7 to 1.4 GtC/yr could be abated by 2050, pushing down emissions to under 4 GtC/yr by 2050.

Figures 12 and 13 display results for Scenario B2 and A1B, respectively (IPCC – SRES). It is possible to conclude that in Scenario B2 emissions may even be lower than in B1, reaching 4.1 GtC/yr by 2050 (or at least around 3.4 GtC/yr with full SAR Forest Model management). For the energy-intensive Scenario A1B, CO_2 emissions by 2050 could be 9.5 GtC/yr (or at least 8.7 GtC/yr using full SAR Forest Model management).

7. Economic Results

The scenario constructed has to be validated by an economic analysis, since the production of very large amounts of energy may be infeasible to subsidize over the long

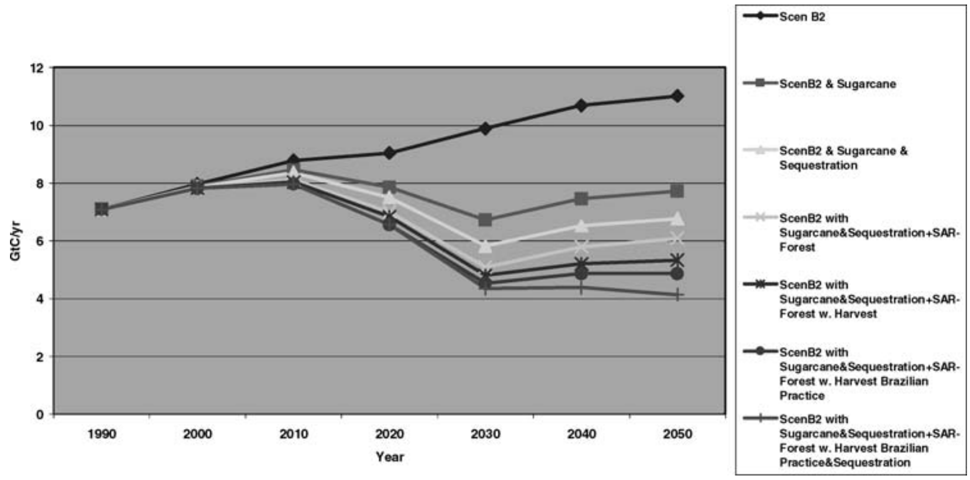

Figure 12. CO_2 energy and land use emissions in scenario IPCC B2, with sugarcane, and with sugarcane plus SAR-Forest. (Source: IPCC 2000 and Author)

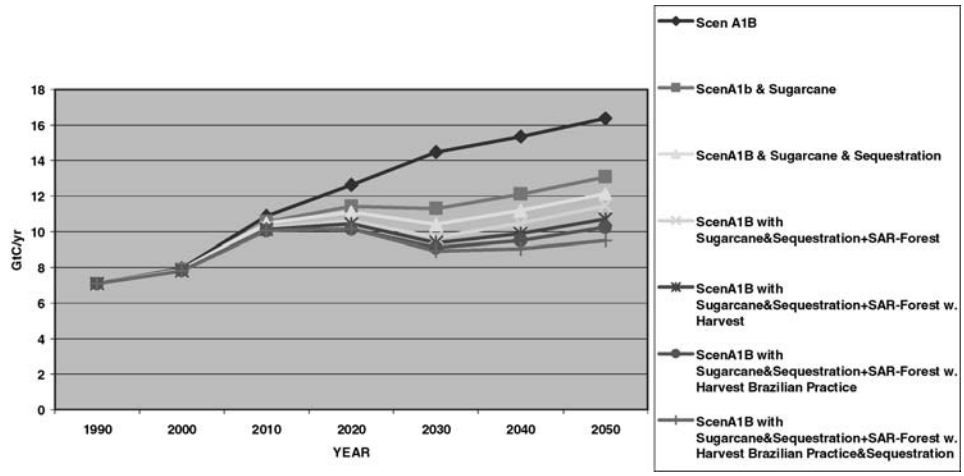

Figure 13. CO_2 energy and land use emissions in scenario IPCC A1B, with sugarcane, and with sugarcane plus SAR-Forest. (Source: IPCC 2000 and Author)

term. Based on present costs of the sugarcane industry in Brazil, and assuming that economies of scales will reduce the cost of such large energy programs, it is possible to estimate full accumulated program investment demand around US$1,100 billion at current undiscounted dollars, assuming no inflation, up to 2030 for sugarcane energy production using a plantation area of 143 Mha (Figure 14) *corresponding to 7700*$/ha.[9] This investment figure is so high that a useful comparison would help to better understand it. As shown in Figure 14 the total value of abated carbon would be US$283 billion if its unitary value were US$10/tC, which is the present

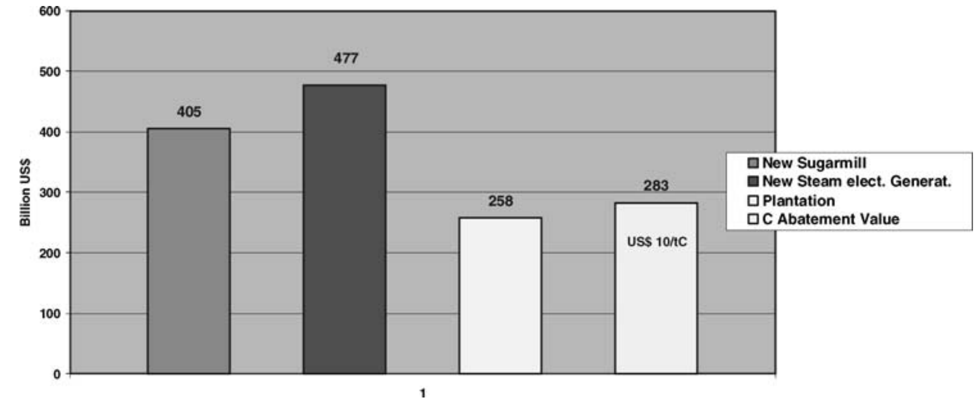

Figure 14. Accumulated investment for alcohol and electricity generation, and value of carbon abated – World 2003–2030. (Source: Author)

market price [this has more than doubled since this paper was prepared – Editor] for Clean Development Mechanism projects. The carbon value currently being commercialized in some closed markets, like the UK, can be as much as US$50/tC.

Figures quoted above represent historical accumulated values in the period 2003–2030 at undiscounted US dollars. Probably a better perception is provided by the present value of the total capital investment per tonne of CO_2 abated. The values are extracted by bringing all investments in biomass plantation, sugar mills and electric generation plants installations carried out during the period 2003–2050 to today's value based in interest rates of 2 and 10%, representing the minimum and maximum expected values for investments in a range of countries. Once present costs are available they are divided by the total amount of CO_2 abated in the period, which is obtained by just adding annual abatements. This is shown in Figure 15, for the two different interest rates and is compared with the extra costs required to construct and operate a natural gas electric generation plant with 500MWe capacity with Carbon Capture and Storage (CCS) technology, at a fuel cost of US$2.5/GJ (using Figures 4 and 6 from Freund and Davison 2002). This comparison is very useful since the use of CCS on a fossil fuel-based power plant may provide similar benefits on GHG emission abatement to a biomass-based one. The comparison only provides a partial view since the values for the sugarcane scenario only includes investment costs for plantation, and processing biomass in liquid fuels and electricity while for the natural gas plant it includes investments and operational costs but only for the CCS activity. Considering that investments on biomass plantation, in sugar mills and in electricity generation plants represent more than 50% of the cost of alcohol and electricity we conclude that when all operational costs are accounted for, the figures for full cost for the sugarcane option shown in Figure 15 will increase by at most a factor of 2. With such corrections added to Figure 15 it is useful to note that the sugarcane alternative has a lower full cost than the CCS alternative

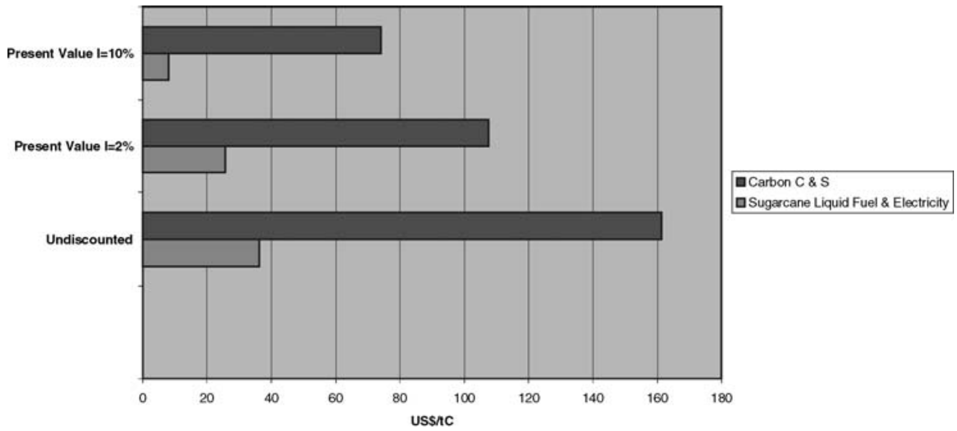

Figure 15. Investment cost for liquid and electricity production from sugarcane compared with additional full cost for carbon capture & storage practice in electricity generation. (Source: Freund and Davison 2002 and Author)

for the natural gas plant and its benefits include significant amount of electricity and liquid fuel production, opposed to CCS figures which accounts exclusively for costs due to CO_2 abatement.

Finally, it is important to discuss the technical and probable economic potential of adding CCS to the large-area sugarcane plantation scenario. During transformation of sugars in ethanol, almost 50% in weight of the fermented material is transformed into CO_2, which is presently vented, since very little market exists for the use of such high-purity CO_2 (Mollersten et al. 2003; Woods et al. 2005). Also, all energy produced in the sugar mill for its own use and for sales to the grid results from biomass burning, which implies further CO_2 emissions reductions. Using the same CCS technology being tested for fossil fuels it is possible to increase the net abatement of C emission as shown in Figure 16 (compare results with Figure 8). Furthermore, remembering that only a very small amount of fossil energy compared with the harvested biomass energy is used for sugarcane plantation and conversion to final forms of energy (Moreira and Goldemberg, 1999; Macedo et al. 2004), it is possible to show that net carbon emission is indeed negative (it is possible to produce energy and simultaneously remove CO_2 from the atmosphere) through the use of sugarcane crop coupled with CCS (Mollersten et al. 2003; Azar et al. 2003).

Regarding the afforestation/reforestation scenario, an average cost of US$7/tC was assumed as valid for all land areas (IPCC 1996). With the purpose of quantifying economic gain from the sales of harvested wood used for electricity generation a net revenue (discounting plantation and harvest costs) of US$10/t of wood was considered.[10] Investment for installation of biomass-based electricity generation plants (using biomass gasification and combined cycle with an efficiency of 40%) was assumed as US$1000/kWe for 50 MWe capacity units.[11] In our model, due to

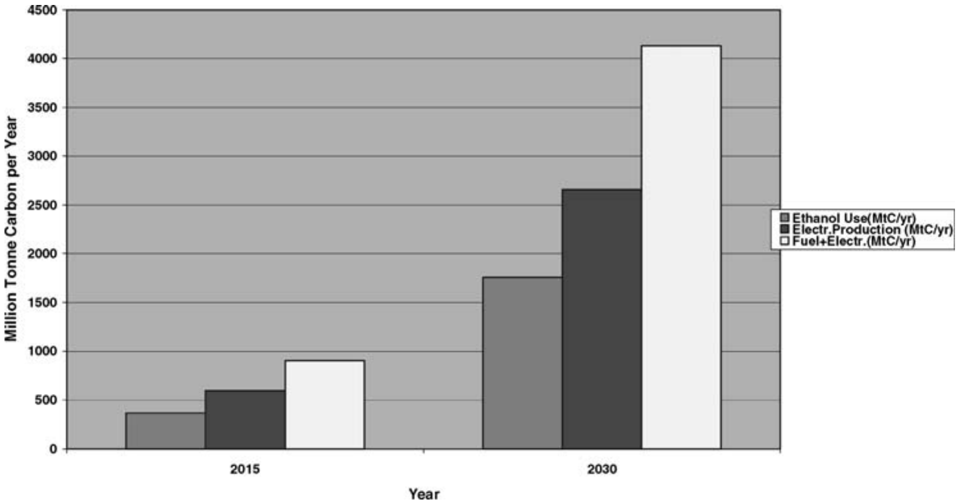

Figure 16. World carbon abatement and sequestration in 2030 (2015) due use of sugarcane biomass in 143 (45) MHA. (Source: Author)

the large amount of power produced, it is assumed that most of the plants will be of a large size (500 MWe) and their costs are scaled up from the 50MWe units' price using a 0.95 factor each time capacity doubles. A value of US$10/tC was assumed to be credited to the project for stored and avoided carbon emission. Figure 17 shows the undiscounted costs for forest implementation and for the associated electricity generation plants, as well as the full revenue from harvested wood and from C abated.

Figure 18 shows the present cost of plantation and present net revenue from wood commercialization for three different situations: no harvesting, harvesting according to a long rotation length (Table V) and when frequent harvesting is considered for Tropical America and Tropical Asia, named Brazilian Eucalyptus Practice in the Figures displayed below.

With a present cost of around US$110 billion it is possible to afforest/reforest 345 Mha of land over a 30 to 50 years timescale (see Table V, 'planting rate' and 'land available' columns) including replanting according to Table V ('rotation length'). When harvesting is added to the SAR Forest Model plantation cost increases, but is compensate by the revenue obtaining from wood commercialization. It is also clear that by using fast-growing trees in Tropical America and Asia (e.g. Brazilian Eucalyptus Practice), cost increases slightly less than for the SAR Model Forest with harvesting and a higher revenue from wood is obtained.

Figure 14 shows that the total investments for the sugarcane plantation has an undiscounted value of US$1140 billion (258 for plantation +405 for sugar mills +477 for power plants) for a period of 27 years. From Figure 17 total investment for afforestation/reforestation is US$996 billion (318 for plantation +678 for power

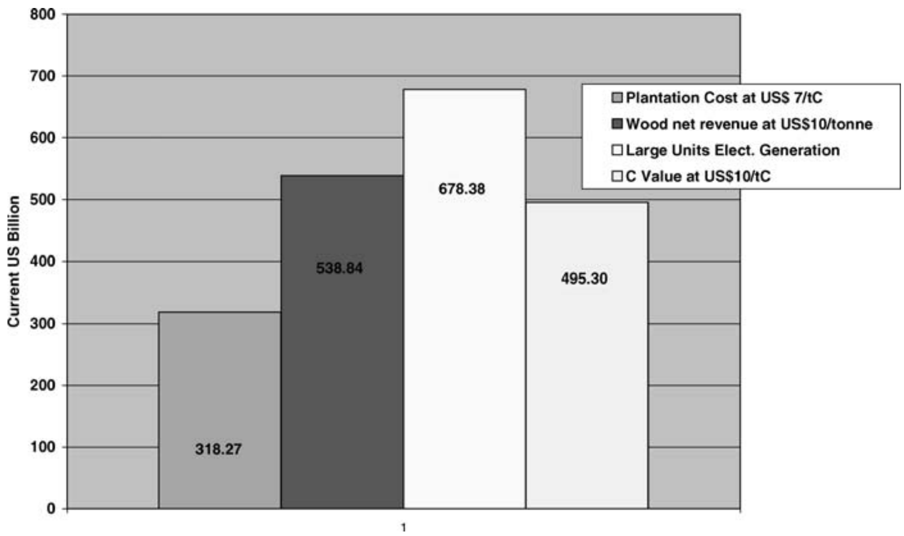

Figure 17. Accumulated investment for electricity generation from forest compared with accumulated revenue from wood commercialization and from credits due carbon abatement – world 2003–2050. (Source: Author)

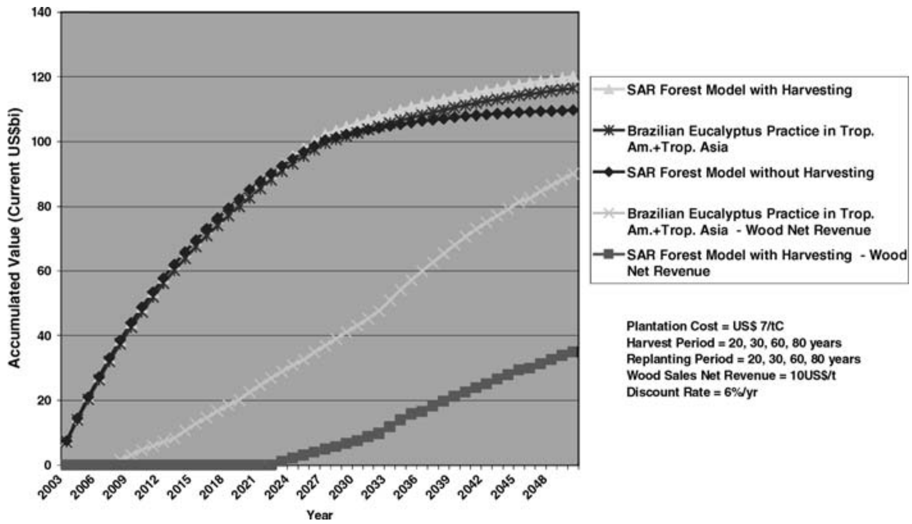

Figure 18. Present value of cummulative plantation expenses and net revenue from wood commercialization for three different practices – SAR forest model. (Source: Author)

plants) for a period of 47 years. A revenue of US$220 billion from carbon mitigation is expected for the former case whereas for the latter one the revenue expected due to carbon mitigation is US$495 billion. Thus, both carbon mitigation efforts together yield a net historical undiscounted investment of US$1421 billion (920 billion for sugarcane and 501 billion for forest), assuming carbon mitigation at a value of US$10/t.

Such high investment values, which provides significant carbon emission mitigation, allows the production of 10,000 TWh/yr from sugarcane, 3,990 TWh/yr from forests, and 16,990 million barrels of oil per year at the end of the time period considered in our scenarios but with almost similar large values since the year 2030. To generated this amount of electricity (13,990 TWh/yr) it would be necessary to install nearly 2000 GWe (with a capacity factor of 80%) requiring an investment of US$1000 billion using natural gas-based combined cycle power units (US$500/kWe) if traditional energy sources had to be relied on. Assuming the balance (1421–1000) is justified by oil investment, its value would be US$24.9 for each annually produced barrel. Since this oil will be produced at near this amount, at least for the period 2030–2050, it represents an investment of US$1.24/barrel of oil (US$24.9/20yrs). This figure for upstream oil investment is very difficult to be obtained by the oil industry (ExxonMobil, 2004). Even more, it's necessary to compare our renewable liquid fuel with gasoline, which means further investment in refineries. Thus, the investment in our biomass scenarios would be probably lower than the one necessary to generate the same amount of energy using fossil fuels.

Finally, in order to better understand the investment required for liquid fuel production and electricity generation it is useful to review Figure 15, where the present investment value for the sugarcane option is US$8/tC (10%/yr discount rate) and Figures 19 and 20 showing a present investment value between $0.5 to $4.5/tC (6% discount rate) for forest plantation and between $2.3 to $2.6/tC (6% discount rate) for investments to install wood-based power plants.

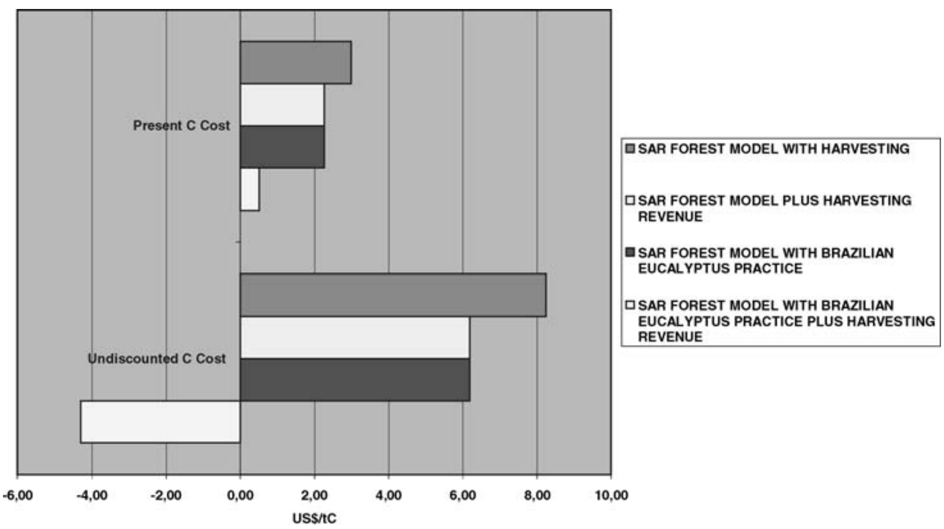

Figure 19. Undiscounted and present value (6%/yr) for several planted forest management. (Source: Author)

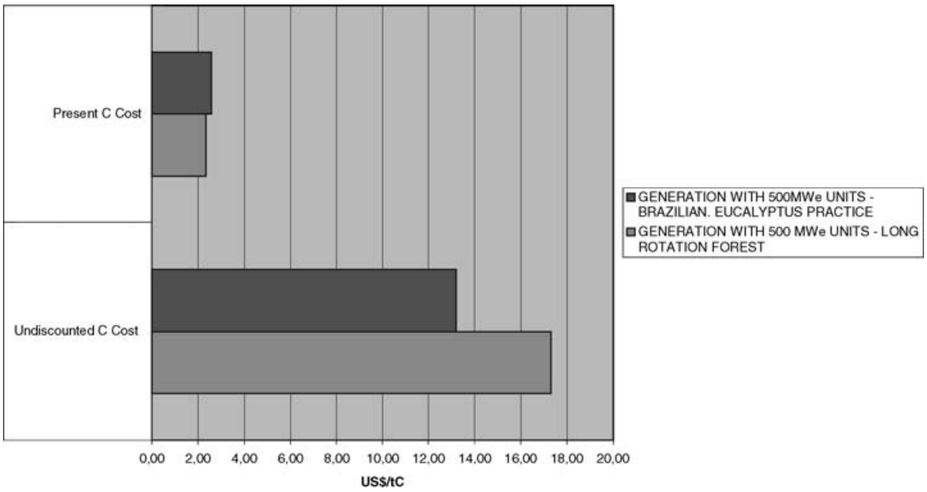

Figure 20. Undiscounted and present value (6%/yr) investment in electricity generation for SAR-planted forest. (Source: Author)

8. Conclusions

The large-scale sugarcane plantation scenario presented in this paper, as well as the SAR Forest Model scenario are intended to demonstrate the significant contribution that biomass energy can provide as a source of renewable energy and as a GHG abatement option. In practice, it will be quite difficult to achieve the entire forecasted results due to the modest or lacking global interest in biomass for energy. This is especially true for sugarcane, which is essentially a crop grown in tropical countries, exactly the ones with shortages of capital and that are lacking in the tradition of significant R&D efforts. Nevertheless, the purpose of this exercise is to show:

1. that biomass energy can be an important source of energy in the short-term, and
2. that, if for some unexpected reason a significant effort in CO_2 mitigation has to be quickly implemented, sugarcane crops coupled with CCS may become extremely important.

Also, in the future it is expected that biomass crops other than sugarcane, e.g. sweet sorghum and palm oil may become a significant source of energy. Conversion of cellulose to ethanol is a technology that, if commercially feasible, can promote large scale production of this liquid fuel even in temperate countries and with much less global environmental impact than with the utilization of biomass from cereals as is currently the case, mainly in the USA. On top of that, it is generally accepted in the literature that GHG mitigation requires the use of almost all technical options available (IPCC 2001), which means that even if biomass future share of the global energy profile is half the amount considered in this paper, it should be possible to reduce future GHG emissions with the help of similar efforts on other potential mitigation alternatives.

Acknowledgement

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Notes

1. Irrigated sugarcane plantation is not being considered in this paper as an option for biomass energy production. Nevertheless, it is used in some countries for commercially feasible sugar production activity showing that investment and operational costs may not be a barrier. Regarding forests such practice does not occur. Thus, under extreme pressure for carbon mitigation alternatives irrigated sugarcane plantations may be considered as a valid option since its water demand is modest.
2. Such crops deserve special attention since on top of their high biomass energy productivity they allow the production of biofuels simultaneously with electricity generation using present practices and technologies. See more details in Section 3.
3. Full accounting of the energy content of cereal residues was carried out by the author using FAO data for the amount of cereals produced and energy content by volume of cereal residues quoted in Hall et al. (1993).
4. It is assumed biomass from forest is converted to electricity with 30% efficiency.
5. Presently (2003 and 2004) neat ethanol cost to consumer is less than half ethanol/gasoline blend in major sugarcane growing states and around 60% in several other states. Preference of flexible-fuel car owners is strongly focused in the use of neat ethanol.
6. Such very high increase in yield is assumed based in a scenario where significant effort at global level will occur due to the difficulty on finding many cost competitive carbon mitigation options in the transportation sector or, mainly, if a consensus is reached about the relevance of avoiding or, at least, of being prepared to face abrupt climate change risks (see section 6 on negative carbon emission). Genetic improvement of sugarcane could be one of the several important R&D results expected from this global effort. Finally, under this scenario irrigated sugarcane could share some responsibility in obtaining the high yield growth if R&D alone falls much below expectation.
7. This is not difficult to achieve. According to the World Energy Assessment Report, the energy required to transport biomass for distances like 50 km is a small fraction of its energy content (Rogner et al. 2000).
8. It is assumed that within a 10 years period it will be possible to store 80 tC/ha for such fast growth trees. This requires a pool of 160 t/ha (with an energy content of 3200 GJ/ha). Considering that the harvesting and regrowth cycle is 6 years and that yield growth is more pronounced in the first years with a tendency to slow down in the last years, approximately 20 t/ha.yr is considered to be feasible for the future decades, mainly if an orchestrated plantation effort is performed. Such yield (400 GJ/ha.yr) is consistent with Figure 5, which shows a final energy from wood-based electricity generation (with 30% conversion efficiency) around 160 GJ_e/ha yr (or 530 GJ/ha.yr of primary energy).
9. This figure includes investment costs for sugarmill construction, for liquid fuel and electricity facility production, and for sugarcane plantation distributed in the period 2003 to 2030.

10. Assuming harvesting and transportation cost around US$5/tonne added to the plantation cost of US$7/tC (approximately US$3.5/t of wood), a tonne of wood has to be sold at a value around US$19 (US$1.0/GJ) to guarantee the US$10 net revenue on wood commercialization. Taking into account interest rate on investment the value can increase to US$1.5/GJ. Since US$1.5/GJ is an acceptable value (Carpentieri et al. 1993), the US$10/tonne profit looks reasonable.
11. This is a very debatable issue. Investment cost in a biomass gasification plant has been evaluated as high as US$2000/kW (IPCC 2001). Nevertheless, this price is expected to decline significantly after some units are constructed. In our scenario we are assuming that hundreds of units of 500 MWe will be constructed. This target requires commercially feasible technology, which justify the low value quoted in the text.

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