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Assessment of sustainable energy potential of non-plantation biomass resources in Sri Lanka

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Abstract

This paper discusses the importance of biomass as a source of energy in Sri Lanka and assesses the sustainable national non-plantation biomass resource potential. Different biomass sources, both direct and indirect, are considered in the analysis. The direct sources include agricultural and wood residues, animal manure, municipal solid waste and wastewater. The indirect sources include fuelwood conservation through efficiency improvements and fuelwood savings through fuel switching. The potential of each source is estimated for the base year 1997 as well as for the years 2005 and 2010. The total energy potential of these sources in 1997, 2005 and 2010 is 120 PJ, 133 PJ and 142 PJ, respectively. The corresponding electricity generation potentials are 8.34, 9.24 and 9.85 TWh, respectively for a conversion efficiency of 25%. The annual electricity demand in Sri Lanka 1997 was 4.20 TWh and the forecast values for the years 2005 and 2010 are 10.50 and 15.60 TWh respectively; this implies that the biomass sources could contribute significantly towards meeting the future electricity requirement.

Keywords: Biomass; Conservation; Fuel switching; Fuelwood conservation and substitution; Residues

1. Introduction

Biomass accounted for approximately 55% of the primary energy consumed in Sri Lanka in 1997 [1]. More than 80% of the biomass consumption in the country is for cooking and heating purposes in domestic and commercial sectors; nearly 90% of the population depends on fuel-wood and other forms of biomass for their daily cooking.

The main objective of the present study is to assess the potential of the non-plantation biomass as sustainable sources of energy. The non-plantation biomass sources considered in this study

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include residues from top ten types of agricultural crops, animal manure, municipal solid waste, industrial waste water, and fuelwood generated from substitution by other fuels and efficiency improvement of current energy systems. The potential of these sources are estimated for the years 1997, 2005 and 2010.

The methodologies to estimate the energy potential of the biomass sources are presented elsewhere [2].

2. Sustainable national biomass resource potential

2.1. Agricultural residues

The agricultural residues selected for the assessment in this study are paddy husk, paddy straw, coconut shells, coconut husks, coir dust, bagasse, sugarcane tops, maize stalk, maize cobs. In addition to these sources, sawdust is also included in the assessment since it has a considerable potential.

2.1.1. Paddy residues: husk and straw

Introduction: Paddy is the most extensively cultivated crop in Sri Lanka. The paddy is grown in two seasons per year: the "Maha" season with harvesting in February and the "Yala" season with harvesting in August. The contribution of the Maha harvest to the total annual production is approximately 65% while that of the Yala harvest is 35%. The total area under paddy cultivation in 1997 was about 730,000 h and the total production was 2.24 Mt [3].

Prediction of production and availability of agricultural residues for 2005 and 2010 is based on certain assumptions. According to the predicted land use pattern in the country [4], the quantity of agricultural land is expected to remains approximately constant, especially land categories for paddy & other annuals, perennials, sugar cane and coconut. However, the productivity would increase due to improved technologies. Therefore it is assumed that the total production of these products in 2005 and 2010 would increase in proportion to the corresponding population increase. The total population in 1997 was 18.55 million and the projected population in 2005 and 2010 is 20.06 and 21.02 million respectively. Based on the above assumptions and projected population, the annual paddy production in 2005 and 2010 is estimated as 2.42 and 2.54 Mt, respectively.

Paddy husk is produced at rice mills; paddy husk production per district cannot be taken directly from the district paddy production figures, as there exists a considerable transfer of paddy between districts. In Sri Lanka, rice mills process more than 2 Mt of paddy annually. There are approximately 7000 rice mills operating throughout the country; of them, 77% are custom mills which do the milling for the farmers who remain the owner of the rice. The balance 23% are commercial mills which purchase the paddy and sell the rice after milling [5]. It is estimated that only 50% of the rice is produced in the commercial mills, and other 50% in the custom mills.

In the Central and Eastern districts, paddy is usually parboiled before milling, while in the Southern districts parboiling is not common. In parboiling mills, paddy husk is used for combustion in boiler; according to an assessment conducted in Anuradhapura and Pollonnaruwa districts, approximately 50% of the paddy husk produced is utilized as fuel for steam generation while 44% is left unutilized. In most of the rice processing areas, the surplus paddy husk is considered as a waste material creating environmental problems and often available free of charge. In some cases, larger mills even pay some money to contractors for taking the husk away regularly. Some of the husk is used in poultry industry and as a fuel in the domestic sector and bricks manufacturing. It is difficult to obtain a complete picture of these present uses and the situation varies from region to region [6]. According to a field survey conducted in the main paddy producing areas in Sri Lanka [5], 54% of paddy husk produced in commercial mills is used for energy applications, 7% is used for other applications and therefore the excess amount available is estimated to be 39%.

At present most of the paddy straw produced are either burned in the field or used as animal feed. A portion also goes to the paper making industry. Paddy straw also plays a vital role as a candidate raw material for biogas production systems which has been developed by various local institutions. Due to the low density and high combustion rate, paddy straw ranks somewhat low as an energy source.

Properties of paddy residues: Paddy husk is a bulky material and existing literature shows considerable variations in its characteristics [7]. Thus, the bulk density of paddy husk may vary from 90 to 110 $kg\,m^{-3}$, the lower heating value (LHV) from 12.5 to 19.5 $MJ\,kg^{-1}$, moisture content from 8.5% to 12.5%. For the present analysis, LHV is taken as 14 $MJ\,kg^{-1}$ and moisture content is assumed to be 9% on wet basis. The properties used in the present analysis are presented in Table 1. Typical fuel analyses (ultimate and proximate analyses) of paddy husk and paddy straw are given in Table 2 [6,8].

Residue to product ratio (RPR): In Sri Lanka, different paddy varieties are cultivated in different localities considering climate, rainfall, soil type etc. and different varieties have different values of RPR. RPR for most commonly grown Sri Lankan paddy varieties varies from 0.18 to 0.23. In the present analysis an average value of 0.20 is taken for RPR of paddy husk.

Available literature shows a considerable range in the value of RPR of paddy straw. The amount of straw produced from paddy depends on several factors such as paddy variety, fertilizer, season, harvesting practices etc. The recently introduced short-stem paddy varieties also produce less amount of straw. Based on Bhattacharya et al.

Table 1
Properties of biomass residues

Product	Residue	RPR	Moisture content-wet basis (%)	LHV ($MJ\,kg^{-1}$)	Energy use factor	Surplus availability factor	Collection factor
Paddy	Paddy husk	0.20	9.0	14.0	0.54	0.39	0.8
	Paddy straw	1.76	12.7	16.0	0.00	0.80	0.6
Coconut nuts	Coconut shell	0.52	8.7	18.1	0.97	0.03	0.8
	Coconut husk	1.03	10.3	18.6	0.03	0.57	0.9
	Coir dust	0.62	15.0	13.4	0.00	0.20	0.9
Sawn wood	Sawdust	0.35	7.0	19.4	0.02	0.98	0.9
Sugar	Bagasse	0.29	20.0	15.4	1.00	0.00	1.0
	Sugar cane top	0.30	11.0	15.8	0.00	1.00	0.7
Maize seeds	Maize stalks	2.00	20.0	12.6	0.00	1.00	0.6
	Maize cobs	0.27	7.5	16.3	0.00	1.00	0.8

Table 2
Fuel analysis of biomass residues

Residue	Proximate analysis (%)[a]			Ultimate analysis (%)					
	Volatile matter	Fixed carbon	Ash	C	O	H	N	S	Ash
Paddy husk	68.5	17.4	14.1	43.1	37.3	4.9	0.5	0.1	14.1
Paddy straw	54.1	24.8	21.1	41.4	39.9	5.0	0.7	0.1	17.4
Coconut shell	73.9	19.6	6.5	—	—	—	—	—	—
Coconut husk	73.0	23.0	4.0	—	—	—	—	—	—
Coir dust	62.0	26.0	12.0	46.0	46.0	7.0	1.0	—	—
Saw dust	82.8	16.5	0.7	51.8	41.3	6.3	0.1	—	0.5
Bagasse	74.1	19.2	6.7	47.0	43.0	6.0	2.0	—	2.0

[a]On dry basis.

[9], the selected value of RPR for the present study is 1.76.

Generation and availability: The total production of paddy in 1997 was 2.24 Mt [3]. Therefore, with a RPR of 0.2, the estimated annual production of paddy husk in 1997 was 448 kt. Based on the projected population, the estimated annual production of paddy is 2.42 and 2.54 Mt in 2005 and 2010 respectively; the corresponding estimated generation of paddy husk is 484 and 507 kt, respectively. With RPR for paddy straw taken as 1.76, the estimated annual generation for the years 1997, 2005 and 2010 is 3.94, 4.26 and 4.47 Mt respectively.

The utilization pattern of the paddy husk generated in the country at present is not well known. However, there are a number of studies on the subject related to certain sectors as discussed above [5,6]. Based on these, the energy use factor and the surplus availability factor of paddy husk are taken as 0.54 and 0.39 respectively. A collection factor of 80% is used for paddy husk, since 50% of the paddy is estimated to be processed in custom mills where there is no proper mechanism for collection.

Above information could be used to estimate the total amount of paddy husk available for energy. For 1997, 2005 and 2010 these amounts are 333, 360 and 377 kt, respectively.

The amounts of paddy straw consumed are estimated based on Sepalage [10]: 6% consumed in paper industry, 4% consumed as animal feed, and 10% consumed for other uses so that the remaining 80% can be regarded as the surplus amount. Therefore, current energy use factor for straw is zero and surplus availability factor is 0.8. Collection of all the paddy straw will be difficult, as it is available in the field in scattered manner. Therefore a collection factor of 60% is assumed for paddy straw. The estimated total amount of paddy straw available for energy application in 1997, 2005 and 2010 is 1.89, 2.05 and 2.14 Mt respectively.

2.1.2. *Coconut residues: shells, husks and coir dust*

Introduction: Coconut is grown extensively in Sri Lanka. The major share of the production is from the so-called "coconut triangle" area, which is bordered by the cities Colombo, Kurunegala and Puttalam. Coconut plantations generate residues such as trunks, fronds (leaves), husks, shells and coir dust.

Coconut shell is used as a fuel for cooking in the household sector. Shell produced from copra making and desiccated coconut manufacturing is partly used for in-house process heat requirement and the rest is mostly used for charcoal manufacturing. Bulk production of coconut husk is used for extracting the fiber. The rest of the husk is buried in plantation sites or used as fuel. The fiber production leaves a large quantity of pith or coir dust which presents a severe disposal problem. They normally accumulate in heaps around the fiber mills and have grown into mountains over the past 60 years; it is estimated that over 20 Mt of coir-dust has accumulated over this period. In the recent years, a new export industry on coir-dust briquetting has developed, the briquettes being used as soil conditioner. This industry is developing rapidly and at present the demand for coir dust exceeds the annual generation.

Total production of coconut in 1997 was approximately 2631 million nuts or 895 kt. Approximately 18% of the production was exported. In order to estimate the production of coconut in 2005 and 2010, it is assumed that the local consumption would increase proportional to the increase in population and the export would remain at 18% of the total production. Based on these assumptions, the estimated total annual production of coconut in 2005 and 2010 is 2845 million nuts (or 967 kt) and 2983 million nuts (1.01 Mt) respectively.

Properties of coconut residues: Moisture content of coir-dust, when discharged from fiber mills, is around 85% on wet basis. After air drying this reduces to 10–15%. The bulk density of coir-dust is approximately 370 $kg\,m^{-3}$ at 85% moisture level and at 15% moisture level this reduces to about 100 $kg\,m^{-3}$. The LHV of coir-dust at 15% moisture content is 13.4 $MJ\,kg^{-1}$.

The LHV of coconut shell is 18.13 $MJ\,kg^{-1}$ at moisture content of 8.7% on wet basis, while that of coconut husk is 18.62 $MJ\,kg^{-1}$ at 10.3% moisture level.

Residue to product ratio (RPR): In Sri Lankan varieties, the weight of the husk of a coconut nut is about 350 g. The fiber is about 140 g and the balance 210 g is coir dust [10]. On an average, the shell of a nut has a dry weight of 177 g. As the average weight of a nut (i.e., the product) is 340 g, RPR of coconut residues could be considered as 0.62 for coir-dust, 0.52 for coconut shell and 1.03 for coconut husk.

Generation and availability: Total estimated production of coconut in 1997, 2005 and 2010 is 895, 967 kt and 1.01 Mt, respectively; the generation of coconut shell amounts to 465, 503 and 527 kt, respectively. At present, almost all of the coconut shell generated is used for energy purposes: 166 kt (i.e. 35.7%) used for charcoal production (both activated charcoal and coconut shell charcoal), 87 kt (i.e. 18.7%) used in copra making industry as a fuel and 200 kt (i.e. 43.0%) used in domestic sector for cooking. Therefore the excess amount is only 2.6%. Accordingly, the energy use factor and the surplus availability factor of coconut shells could be considered as 0.97 and 0.03, respectively. Further, a collection factor of 80% is taken in the present analysis, as most of the excess shells are available in households in rural areas. Then the amounts of coconut shells available for energy in 1997, 2005 and 2010 are 372, 402 and 422 kt, respectively.

Assuming a RPR value of 1.03, the annual generation of coconut husk is estimated as 922 kt in 1997, 996 kt in 2005 and 1.04 Mt in 2010. Presently, 368 kt (39.9%) of coconut husk is used in fiber extraction industry and 31 kt (3.4%) is used for domestic cooking. Therefore the energy use factor and the surplus availability factor of coconut husk could be considered as 0.03 and 0.57, respectively. The collection factor for coconut husk is considered to be 90%. As in the case of coconut shells, it is assumed that the 50% of cook stoves which use coconut husk are traditional and conversion of these stoves to improved cook stoves save 50% of fuel. Based on these assumptions, the total amounts of coconut husk available for energy applications are 497, 537 and 564 kt for the years 1997, 2005 and 2010, respectively.

About 40% of husk produced is utilized in the industry. Based on this information together with a RPR of 0.62, the total annual generation of coir-dust is estimated to be 221 kt in 1997, 239 kt in 2005 and 251 kt in 2010, at a moisture level of 85%. The corresponding amounts of air-dried coir-dust with a moisture level of 15% are 39, 42 and 44 kt, respectively. At present, the amount of coir-dust used for energy applications is insignificant. With the rapid development in the coir-dust briquetting industry, the demand for coir-dust has increased significantly. In fact, at present the amount of exports of coir-dust products exceeds the annual generation. However, it is expected that the market for improved coir-dust products will dominate in future; it is estimated that around 20% of separated finer particles of coir-dust will be available for other applications. Based on this, the amount of coir-dust consumed in other uses including briquetting industry is taken as 80% in the present study. Then the energy use factor and the surplus availability factor of coir-dust become 0.0 and 0.2, respectively.

The collection factor for coir-dust is considered to be 90%. Based on this the total amount of coir-dust (with a moisture content of 15%) available for energy applications in 1997, 2005 and 2010 is 7, 8 and 8 kt respectively.

2.1.3. Sawdust

Introduction: In Sri Lanka, there are more than 4000 saw mills. The number of major sawmills is about 380 and minor saw mills is about 500. In addition there are 680 mills owned by furniture manufacturers. The rest of the saw mills are based on manual sawing. Around 55% of the sawnwood are produced at major sawmills, with an average annual output of 750 m^3 per mill [4].

At present, only a small amount of sawdust is used in the manufacturing industry and household sector as a heat source. Most of the sawdust generated is freely available in large heaps around the sawmills creating disposal and environmental problems. Sawdust can be directly burned or it can be converted into briquettes, with or without binding agent.

Properties of sawdust: Sawdust is a bulky material with a density of 370 $kg\,m^{-3}$ [11]. Moisture content of air-dried sawdust is around

6.5–7.5% on wet basis with an average LHV of 19.4 MJ kg^{-1}.

Residue to product ratio (RPR): Around 12% of sawlog input is generated as sawdust during milling operation and only 34% of the input is converted into sawn wood. Therefore RPR of sawdust, i.e. the sawdust to sawn wood ration, could be considered as 0.35.

Generation and availability: In 1997, the total sawn wood demand of the country was 590 kt [4]; therefore the total sawdust generated is estimated to be 207 kt. The predicted generation of sawdust in 2005 and 2010 is 210 and 212 kt, respectively [12].

At present, very small amount of sawdust is used in manufacturing industry and household sector as a heat source. It is assumed that this amount is approximately 2% and the excess is available for future energy applications. That is the energy use factor is 0.02 and the surplus availability factor is 0.98. A collection factor of 0.9 is selected for the present analysis. The total sawdust available for energy in 1997, 2005 and 2010 is estimated to be 185, 189 and 191 kt respectively.

2.1.4. Sugarcane residues: bagasse and sugar cane tops

Introduction: Sri Lanka has three large sugar mills. The total production of sugarcane in 1997 was 775 kt. The total local production of sugar in 1997 was 63 kt, which is just over 10% of the total consumption in Sri Lanka.

Properties of sugarcane residues: Fresh bagasse produced contains 40–55% moisture on wet basis. At 50% of moisture level, LHV of bagasse is about 8.6 MJ kg^{-1}. Air-dried bagasse with moisture content of 20% on wet basis has a LHV of 15.4 MJ kg^{-1}. Moisture content of fresh sugarcane tops is also approximately equal to 50%. LHV of air-dried sugarcane tops at a moisture level of 11% on wet basis is approximately 15.8 MJ kg^{-1}.

Residue to product ratio (RPR): Residue to product ratio of bagasse is taken as 0.29 in the present study [9] and that of sugarcane tops is considered to be 0.3 [13].

Generation and availability: At present, there is no major programme for developing the capacities of the sugar factories. Therefore the total production in 2005 and 2010 is taken as the same amount as in 1997; then annual generation of bagasse and sugarcane tops, with a 50% moisture content, becomes 225 and 233 kt, respectively.

All bagasse produced in the factories is burned in boilers to produce process steam and electricity demand in the factory. No excess bagasse is available for other applications. Thus the energy use factor is 1.0 and the surplus availability factor is zero. The total bagasse available for energy is 225 kt at a moisture level of 50% or 141 kt at a moisture level of 20% in each year. Note that, although bagasse is almost totally consumed in the sugar mills, the present technology used in the industry to produce steam is conventional and inefficient. Therefore there is a considerable potential for energy conservation via introduction of improved technologies, and the surplus energy could be utilized to generate electricity for export to the national grid. The total amount of sugarcane tops are usually kept or burnt at the field. Therefore the entire amount is potentially available for future energy applications. Therefore the energy use factor is zero and the surplus availability factor is 1.0; the collection factor of 70% is assumed for sugarcane tops. Based on these considerations the annual availability of sugarcane tops for energy application is estimated to be 163 kt at a moisture level of 50% or 91 kt at a moisture level of 11%.

2.1.5. Maize residues: stalk and cob

Introduction: The main cereals cultivated in Sri Lanka (other than paddy) in 1997 were maize (26 kt), kurakkan (4 kt), meneri (100 t) and sorghum (200 t) [3]. Maize is the most important among these, and is selected for the present study. The main forms of maize residues are maize stalks and maize cob.

Properties of maize residues: The LHV of maize stalks is taken as 12.6 MJ kg^{-1} at 20% moisture content on wet basis and the corresponding value of maize cobs is 16.3 MJ kg^{-1} at 7.5% moisture content on wet basis [9].

Residue to product ratio (RPR): In the present study, RPR values of maize stalk and maize cobs are taken as 2.0 and 0.27, respectively.

Generation and availability: Total production of maize in 1997 was 26 kt. Based on the population increase, the estimated production in the years 2005 and 2010 are 28 and 29 kt, respectively. Then the total generation of maize stalk in 1997, 2005 and 2010 is estimated to be 52, 56 and 58 kt, respectively, with corresponding generation of maize cob of 7, 8 and 8 kt, respectively. At present no significant applications of maize residues are reported and it is assumed that the entire amounts are potentially available for future energy applications. However, a collection factor of 0.6 is assumed for maize stalk, since it is a field-based residue. In the case of maize cobs, a collection factor of 0.8 is used as a considerable percentage of maize is processed and utilized in domestic sector.

The estimated availability of maize stalk in 1997, 2005 and 2010 is 31, 34 and 35 kt, respectively, while maize cobs is approximately equal to 6 kt, in each of these years.

2.1.6. *Energy potential of agricultural residues*

Tables 1 and 2 show the properties and fuel analysis of biomass residues considered in this study. The estimated total annual availability of agricultural residues and sawdust for energy are presented in Table 3. The total energy potential of biomass residues is estimated to be about 59, 63 and 65 PJ in 1997, 2005 and 2010 respectively.

2.2. *Animal manure*

Introduction: In Sri Lanka the important animals are cattle, buffalo, pig, goats and poultry (chicken & ducks). Other livestock includes sheep and horses, but their numbers are comparatively small. Livestock farms produce polluting wastes. Traditionally their disposal has been by direct use as fertilizers or in some instances by landfilling. These methods cause severe environmental problems such as odour, contamination of water, methane emission etc. For the present study only cattle, buffalo, chicken and goat are considered, in addition to human beings.

Livestock population in Sri Lanka: The figures available at the Ministry of Fisheries & Aquatic Resources and Department of Census & Statistics reveal that the number of animals has not changed

Table 3
Total potential of biomass residues for future energy applications

Residue type		Annual production of the product[a] (kt)			Total potential of biomass residues for future energy applications					
		1997	2005	2010	kt[b]			PJ[c]		
					1997	2005	2010	1997	2005	2010
Field-based	Paddy straw	2239	2421	2537	1892	2045	2143	30.26	32.73	34.29
	Sugarcane top	775	775	775	91	91	91	1.45	1.45	1.45
	Maize stalks	26	28	29	31	34	35	0.39	0.42	0.44
Process-based	Paddy husk	2239	2421	2537	333	360	377	4.66	5.04	5.28
	Coconut shell	895	967	1014	372	402	422	6.73	7.28	7.64
	Coconut husk	895	967	1014	497	537	564	9.24	9.99	9.37
	Coir dust	895	967	1014	7	8	8	0.09	0.10	0.11
	Saw dust	590	600	606	185	189	191	3.59	3.67	3.71
	Bagasse	775	775	775	141	141	141	2.17	2.17	2.17
	Maize cob	26	28	29	6	6	6	0.09	0.10	0.10
Total					3555	3813	3977	58.69	62.94	64.55

[a]The product corresponds to each biomass residue specified in Table 1.
[b]Total weight of each biomass residue is based on the moisture content given in Table 1.
[c]Total energy potentials are calculated based on the Lower Heating Values given in Table 1.

significantly during the past 15 years, except a small downward trend for buffalo and a small upward trend for poultry. Therefore it may be assumed that the total numbers of livestock will remain constant during the period of present study. In 1997, the numbers of animals in millions were 1.58 cattle, 0.73 buffalo, 9.24 chicken, 0.06 duck, 0.52 goat, 0.08 pig and 0.01 sheep [3].

The total population in 1997, 2005 and 2010 is assumed to be 18.55, 20.06 and 21.02 million, respectively. A collection factor of 0.8 is taken for human wastes.

Livestock manure parameters: Accurate estimation of values of different characteristics of animal manure, such as dry matter, fraction recoverable as well as physical & chemical properties is difficult. The values selected for the present study are given in Table 4. The heating value of the biogas is taken as 20 MJ m^{-3}.

Energy potential of animal manure: The estimated amount of animal manure recoverable, the potential of biogas production and the total potential of energy from animal manure are presented in Table 4. The total annual potential of biogas from animal manure in 1997, 2005 and 2010 is 315.2, 320.5 and 323.9 million m^3, respectively, and the corresponding energy potential is 6.30, 6.41 and 6.48 PJ, respectively.

2.3. Fuelwood saving through efficiency improvement

Introduction: In Sri Lanka, the largest consumer of biomass fuels is the household sector. Further, many industries such as agro-industry (tea, rubber and coconut processing), manufacturing industry (brick, tile, lime etc.), and certain establishments in the commercial sector (bakery, hotel, eating houses, etc.) use biomass fuels for process heating and drying. In addition, there are a number of small scale industries which use bio-energy; these includes pottery, ceramic, chemical, metal, textile, distilleries, crop & fish drying, laundries, paddy parboiling, etc. Most of the biomass energy systems used are conventional and therefore inefficient.

In 1997, the estimated consumptions of fuelwood in different sectors were 8.35 Mt in domestic sector, 515 kt in agro-industry, 150 kt in manufacturing industry and 262 kt in commercial sector [4]. Due to the inefficiencies inherent in these industries, there is room for minor and often major improvements in efficiency.

Fuelwood consumption in domestic sector: In Sri Lanka, fuelwood is the major source of energy used in household sector basically for cooking and heating purposes. Most of the cook stoves

Table 4
Total potential of animal manure for future energy applications

Parameter	Cattle	Buffalo	Chicken	Goat	Human		
					1997	2005	2010
No. of animals (million)	1.58	0.73	9.24	0.52	18.55	20.06	21.02
Amount of dry matter DM (kg head^{-1} day^{-1})	2.86	2.53	0.04	0.55	0.09	0.09	0.09
Fraction recoverable	0.5	0.5	0.9	0.3	0.8	0.8	0.8
Recoverable dry matter (kt year^{-1})	824	335	121	31	488	527	552
Fraction of volatile solid (kg VS kg^{-1} DM)	0.93	0.80	0.47	0.60	0.67	0.67	0.67
Biogas yield (m^3 kg^{-1} of VS)	0.20	0.30	0.18	0.31	0.20	0.20	0.20
Biogas potential (Mm^3 year^{-1})	153.29	80.45	10.27	5.84	65.33	70.64	74.02
Annual energy potential (PJ)	3.07	1.61	0.21	0.18	1.31	1.41	1.48
	1997		2005		2010		
Total biogas generation (Mm^3 year^{-1})	315.18		320.49		323.87		
Total energy potential (PJ year^{-1})	6.30		6.41		6.48		

currently used could be categorized to three main types: open-fire three-stone, semi-enclosed (both of which are traditional cook stoves) and improved cook stoves (ICS). Since late seventies, various governmental and non-governmental organizations have launched ICS programmes with the objective of conserving fuelwood and also improving indoor environment. As a result, a number of ICS have been designed and disseminated, for examples Sarvodaya two-pot stove, CISIR single-pot stove, IDB single-pot stove, Anagi-1 (single-pot), Anagi-2 (two-pot) and NERD Center single-pot stove. The most widely used ICS type is the Anagi-2 stove.

In order to estimate the biomass saving potential in the domestic sector, the total fuel consumption of the different types of cook stoves and their efficiencies are needed. For this estimation, three types of stoves have been selected and their average efficiencies have been assumed: open-fire three-stone stoves with efficiency of 9%, semi-enclosed stoves with efficiency of 13% and improved cook stoves (ICS) with efficiency of 18% [14]. It has been estimated that, in 1997 approximately 97% of the population in rural areas used fuelwood for cooking and the corresponding percentage in urban areas was 78% [4]. Noting that 79% of the total population of the country live in rural areas the national percentage of population using fuelwood for cooking is 93%. According to a recent survey conducted by the Energy Conservation Fund (ECF) the utilization pattern of the three categories of stoves in rural areas is: three-stone—47%, semi-enclosed—32% and ICS—21%. The corresponding percentages in urban areas are 56%, 31% and 13%, respectively. From these data, it is estimated that approximately the percentage shares of fuelwood consumed in the three categories of stoves are: 60% in three-stone cook-stoves, 28% in semi-enclosed stoves and 12% in ICS [15].

Fuelwood saving potential in domestic sector: Using the calculated values of fuelwood consumption and efficiencies cited above for different types of stoves, the estimated saving potential of fuelwood is given in Table 5. The estimated total fuelwood consumption in the domestic sector for the years 1997, 2005 and 2010 is approximately 8.35, 8.63 and 8.76 Mt, respectively [4]. The total fuelwood demand was estimated in forestry sector master plan (FSMP) based on three basic assumptions: (a) per capita consumption of fuelwood will decrease by 0.3% per year, as a result of substitution and improved energy efficiency, (b) the percentage of the population using fuelwood will decrease by 0.2% per year up to 1999 and by 0.3% per year during 2000–2020. This change is expected to be brought about by the urban population switching from fuelwood to LPG in the early years and to electricity in later years, and by increased rate of urbanization. This implies that some degree of fuelwood saving through efficiency improvements is already included in the estimated fuelwood demands in 2005 and 2010 given above. Therefore the utilization pattern and the share of fuelwood of the three stove categories derived in the previous section should be modified to accommodate the basic assumptions in FSMP.

Based on the data provided in FSMP [4] and the utilization pattern of different cook stoves in the

Table 5
Fuelwood saving potential in cook stoves

Type of stove	Efficiency (%)	Share of fuel wood (%)			Consumption of fuelwood (Mt year^{-1})			Annual fuelwood saving potential					
								Mt			PJ		
		1997	2005	2010	1997	2005	2010	1997	2005	2010	1997	2005	2010
Three-stone	9.0	60.4	55.3	52.4	5.04	4.77	4.59	2.52	2.39	2.30	37.82	35.79	34.45
Semi-enclosed	13.0	27.4	31.0	33.0	2.29	2.68	2.89	0.64	0.74	0.80	9.53	11.16	12.03
ICS	18.0	12.2	13.7	14.6	1.02	1.18	1.28	0.00	0.00	0.00	0.00	0.00	0.00
Total					8.35	8.63	8.76	3.16	3.13	3.10	47.35	46.95	46.48

base year 1997, the utilization patterns and shares of fuelwood in 2005 and 2010 are estimated. The shares of fuelwood used in three-stone, semi-enclosed and ICS in 2005 are 55.3%, 31.0% and 13.7%, respectively, and the corresponding shares in 2010 are 52.4%, 33.0% and 14.6%, respectively (see Table 5).

Replacement of TCS by ICS would result in total annual biomass saving of 3.16, 3.13 and 3.109 Mt in 1997, 2005 and 2010 respectively; with a heating value of 15 MJ kg^{-1}, corresponding annual energy saving potential becomes 47.35, 46.95 and 46.48 PJ, respectively.

Fuelwood consumption in industrial and commercial sectors: The tea processing industry is the largest industrial consumer of biomass. Almost all of the fuelwood is consumed in wood fired furnaces for drying (and weathering) of tea. The total biomass requirement in coconut industry during 1997 was utilized in fuelwood furnaces (45%), coconut shell fired copra kiln (40%), fuelwood boilers (12%) and carbonization gas fired furnaces (3%). The rubber processing industry employs fuelwood furnaces (80%) and fuelwood boilers (20%). The tobacco industry uses fuelwood barns (80%) and paddy husk fired barns (20%). Bagasse fired boilers are available only in the sugar industry. Brick, tile, lime, pottery and bakeries use fuelwood kilns for their production processes. The distilleries use fuelwood furnaces (80%) and paddy husk fired boilers (20%) in the manufacturing process. Paddy processing industry utilizes paddy husk fired boilers for parboiling operation [16].

The estimated annual fuelwood consumption in bakeries in 1997 was 99 kt and it is predicted that for the years 2005 and 2010 this quantity will remain nearly the same [4]. The fuelwood requirements of tea, rubber and coconut industries in 1997 were 402, 72 and 41 kt, respectively. In 1997 manufacturing industries (brick and tile) consumed 150 kt of fuelwood. It has been estimated that the fuelwood requirements of rubber and manufacturing industry would remain the same in 2005 and 2010 and there would be reductions in other sectors, mainly due to technological changes. The estimated fuelwood consumptions in tea and coconut industries in 2005 are 386 and 33 kt, while the corresponding figures for 2010 are 376 and 26 kt, respectively [4].

Fuelwood saving potential in industrial and commercial sectors: It is assumed that the fuelwood saving potentials in bakery ovens, industrial boilers, industrial furnaces and kilns are 40%, 10%, 35% and 35%, respectively. The estimated total annual fuelwood saving potentials in industrial and commercial sectors are given in Table 6. For the estimation of energy potential, a heating value of 15 MJ kg^{-1} is taken for fuelwood.

The total fuelwood saving potential in industrial and commercial sectors in 1997, 2005 and 2010 is 261, 254 and 250 kt, respectively; the corresponding energy potentials are 3.92, 3.82 and 3.75 PJ, respectively.

2.4. Municipal solid waste (MSW)

Introduction: The availability of MSW in Sri Lanka from different districts has been

Table 6
Fuelwood saving potential in industrial and commercial sectors

Device	Fuelwood consumption (kt $year^{-1}$)			Saving potential (%)	Annual fuelwood saving potential					
					kt			PJ		
	1997	2005	2010		1997	2005	2010	1997	2005	2010
Bakery ovens	99	99	99	40	40	40	40	0.59	0.59	0.59
Boilers	19	18	18	10	2	2	2	0.03	0.03	0.03
Furnaces	478	458	455	35	167	160	156	2.51	2.41	2.34
Kilns	150	150	150	35	53	53	53	0.79	0.79	0.79
Total saving potential					261	254	250	3.92	3.82	3.75

reported in a recent study [17], the total estimated amount being 2.43 kt day^{-1}. The main contribution to this amount is from Colombo district, where the amount is 1.15 kt day^{-1}. A major part of MSW generated is too diffused to be worth collecting. Even in Colombo suburbs, the fraction collected is approximately 10%. In rural areas with low population densities, local authorities do not have solid waste collection mechanism and in many areas people simply bury waste within their compounds.

For this study, MSW generation is assumed to be as 0.75 kg capita^{-1} day^{-1}. From this value, the total MSW generated in the urban sector could be estimated as 2.92 kt day^{-1} in 1997. In the present analysis, it is assumed that only MSW generated in the urban sector could be collected for landfill. With the increase of population, urbanization and improvements in solid waste collection mechanisms there would be a continuous increase in the generation and availability of municipal solid wastes in the future. The generation of MSW in 2005 and 2010 are estimated based on the population, with a generation rate of 0.75 kg capita^{-1} day^{-1} and assumed urban sector population of 21%. The fractions of MSW landfilled in 2005 and 2010 are assumed to be 90%. The estimated availability of MSW for landfill in 2005 and 2010 is 2.84 and 2.98 kt day^{-1}, respectively.

Energy potential of MSW : It is assumed that the calorific value of CH_4 is 50 MJ kg^{-1}. As shown in Table 7, the estimated CH_4 generation in 1997, 2005 and 2010 are approximately 74.4, 90.6 and 94.9 kt year^{-1}, respectively; the total annual energy potential of MSW then becomes 3.72, 4.53 and 4.75 PJ, respectively.

2.5. Wastewater

Introduction: At present, the amount of wastewater treated by anaerobic systems in Sri Lanka is insignificant. In order to predict the total energy potential of industrial wastewater, the fraction of wastewater treated by anaerobic systems for the year 1997, 2005 and year 2010 is taken as 0.60, 0.80 and 0.90, respectively.

Energy potential of wastewater: Table 8 shows the wastewater generated in different industries and the corresponding methane producing capacity. The estimated total potential of energy from wastewater is also shown in Table 8. The estimated annual potential of CH_4 production in 1997, 2005 and 2010 is 3.93, 5.94 and 6.92 kt respectively, and the corresponding total energy potential is 196, 297 and 346 TJ, respectively.

2.6. Fuelwood saving potential through substitution by other fuels

2.6.1. Introduction

The types of biomass that can be substituted by other fuels are mainly woody biomass (fuelwood, charcoal, waste wood) and agro-wastes (crop residues and animal manure). Estimating the amount of biomass fuels that can be generated through such substitution involves the determination of the current consumption pattern and the factors that could affect the rate of substitution. In this paper, only fuelwood is considered to be substituted by other fuels. Current and future consumptions of fuelwood in different devices, both in domestic and industrial sectors, are given in Tables 5 and 6. The possible substitutes for fuelwood are kerosene, liquid petroleum gas

Table 7
Energy generation potential of MSW

Year	MSW Generated (kt day^{-1})	Fraction of landfill	Fraction of DOC in MSW	CH_4 potential (kt year^{-1})	Energy potential (PJ)
1997	2.42	0.80	0.17	74.7	3.72
2005	3.16	0.90	0.17	90.6	4.53
2010	3.31	0.90	0.17	94.9	4.75

Table 8
Energy generation potential of industrial wastewater

Industry	Year	Wastewater generation (Mm^3 $year^{-1}$)	COD ($kg\,m^{-3}$)	Fraction treated in anaerobic systems	CH_4 production potential ($kt\,year^{-1}$)[a]	Energy potential[b] (TJ)
Distilleries	1997	0.30	25	0.6	0.94	47
	2005	0.30	25	0.8	1.26	63
	2010	0.30	25	0.9	1.41	71
Food & beverages	1997	1.50	3	0.6	0.54	27
	2005	2.06	3	0.8	0.99	49
	2010	2.50	3	0.9	1.35	68
Tanning	1997	0.59	5	0.6	0.35	18
	2005	0.59	5	0.8	0.47	24
	2010	0.59	5	0.9	0.53	26
Desiccated coconut	1997	0.45	6	0.6	0.32	16
	2005	0.45	6	0.8	0.43	22
	2010	0.45	6	0.9	0.46	24
Rubber processing	1997	1.77	6	0.6	1.27	64
	2005	2.22	6	0.8	2.13	106
	2010	2.22	6	0.9	2.39	120
Textile	1997	2.59	1.6	0.6	0.50	25
	2005	2.59	1.6	0.8	0.66	33
	2010	2.59	1.6	0.9	0.75	37
Total				1997	3.93	196
				2005	5.94	297
				2010	6.92	346

[a]Methane producing capacity of wastewater in distilleries is taken as 0.21 kg $CH_4\,kg^{-1}$ COD and other industries as 0.20 kg $CH_4\,kg^{-1}$ COD.
[b]LHV of CH_4 is taken as 50 $MJ\,kg^{-1}$.

(LPG) and to a lesser extent electricity. In industrial sector, furnace oil, diesel and LPG could substitute fuelwood in boilers, furnaces and ovens.

2.6.2. Development of the scenarios of substitution

Household sector: Household incomes in Sri Lanka are rising, as is the number of people who can afford to buy gas or electric stoves. These trends will reduce the demand for fuelwood in the medium and long terms. Between 1981 and 1991 the consumption of LPG increased tenfold. Several household surveys have indicated that householders prefer LPG and electricity to fuelwood for ease of use, but cost of purchasing stoves is excessive for poor households, who in fact are the ones suffering from energy shortage. The high price of electricity and the cost of stoves make electricity an alternative only for affluent families. Therefore only LPG and kerosene are considered under the present study as substitutes for fuelwood in household sector which could make impacts at national level. These aspects have been considered in estimating the future fuelwood demand in domestic sector given in Table 5 [4].

Forest Sector Master Plan of Sri Lanka [4] assumed that the percentage of the population using fuelwood will decrease by 0.2% per year up to 1999 and by 0.3% per year in 2000–2020, due to switching from fuelwood to other fuels. Further, it was assumed that the per capita fuelwood consumption will decrease by 0.3% per year (due to fuel switching and improvements in efficiency). These values are conservative estimates and fuel

Table 9
Energy saving potential through fuel switching

Year	Total consumption (Mt year^{-1})				Fuelwood saving potential				
	Household sector		Industrial and commercial sectors		Household sector		Industrial and commercial sectors		Total
	With fuel switching	Without fuel switching[a]	With fuel switching	Without fuel switching[a]	kt	PJ	kt	PJ	PJ
1997	8.35	8.35	0.99	0.99	0.0	0.0	0.0	0.0	0.0
2005	8.17	8.63	0.88	0.93	460	6.95	55	0.83	7.77
2010	7.82	8.76	0.81	0.90	940	14.15	88	1.32	15.47

[a]FSMP [4].

substitution has accelerated since 1990s. Therefore, in the present estimations, it is assumed that the percentage of population using fuelwood will decrease annually by 1.0% from 1997 to 2005 and by 1.5% from 2005 to 2010. The per capita fuelwood consumption is taken to be remains at 0.3% per year, which is assumed to be due to fuel switching.

Industrial sector: In industry too, there is a tendency for substitution of fuelwood by other fuels such as furnace oil, LPG, Diesel and even electricity in spite of their prices. In the present study LPG and furnace oil are considered as possible substitutes for fuelwood in industrial sector.

Future fuelwood demand in the industrial and commercial sector predicted by FSMP [4] shows a slow decline (approximately 0.7% per year), due to improved efficiency and technological change (fuel switching). Therefore fuelwood saving through fuel switching is included in the projected fuelwood requirement given in Table 6. However, as in the domestic sector, fuel switching from fuelwood to other fuels has been taking place at a higher rate than predicted by FSMP [4]. In the present study, it is assumed that the fuel switching will take place at a constant rate of 1.5% per year from 1997 to 2010.

2.6.3. *Energy potential of fuelwood saved by substitution*

According to the present study, percentage of population using fuelwood for cooking will reduce from 93.0% in 1997 to 85.8% in 2005 and 79.6% in 2010, while the per capita consumption will reduce from 1.33 kg day^{-1} in 1997 to 1.30 kg day^{-1} in 2005 and 1.28 kg day^{-1} in 2010. The total annual fuelwood demands for cooking in the domestic sector is estimated to be 8.35, 8.17 and 7.82 Mt in 1997, 2005 and 2010, respectively. As the corresponding fuelwood demand estimated by FSMP [4] are 8.35, 8.63 and 8.76 Mt, the fuelwood generations through switching to other fuels is zero in the base year 1997, 463 kt in 2005 and 943 kt in 2010. The corresponding energy generation potential in 2005 and 2010 is 6.95 and 14.15 PJ respectively.

In industrial and commercial sectors, fuelwood demand would decrease from 988 kt in 1997 to 875 kt in 2005 and to 812 kt in 2010, as predicted by the present study (see Table 9). This would result in fuelwood generation of 55 kt in 2005 and 88 kt in 2010 with annual energy potential of 0.83 and 1.32 PJ respectively.

3. Conclusions

A large potential exists for using different types of non-plantation biomass resources for modern energy applications in Sri Lanka. Use of these sources for modern energy applications is also associated with social and environmental benefits. The direct sources considered in the present analysis include agricultural residues, animal manure, municipal solid wastes and industrial

Table 10
Total bio-energy potential for future energy applications

Type of resource	Total biomass resource potential for future energy applications					
	Mt (or Mm^3)			PJ		
	1997	2005	2010	1997	2005	2010
Agricultural residues	3.56	3.81	3.98	58.69	62.94	64.55
Animal manure (Biogas)[a]	315.18	320.49	323.87	6.30	6.41	6.48
Biomass conservation	3.42	3.38	3.35	51.27	50.77	50.23
MSW (CH_4)	0.07	0.09	0.10	3.72	4.53	4.75
Waste water (CH_4)	0.0	0.01	0.01	0.20	0.30	0.35
Fuel switching	0.0	0.52	1.03	0.0	7.77	15.47
Total				120.18	132.72	141.83

[a]Biogas amount is in Mm^3.

wastes, which remain mostly unutilized at present. Under biomass residues, field-based residues have the major energy potential; however these have other uses and their collection is difficult so that these are less feasible for energy use.

In addition to direct sources, a large quantity of biomass could be saved for modern applications through efficiency improvements of current applications, as almost all the biomass energy systems employed are traditional and therefore inefficient. In this case the major contribution comes from domestic cooking as the household sector is the main consumer of biomass in the country. This shows the importance of further studies and surveys on development and dissemination of efficient cookstoves in the country. A summary of the energy potential of all non-plantation biomass resources is presented in Table 10. The estimated total annual energy potentials in 1997, 2005 and 2010 are 120, 133 and 142 PJ, respectively. With a conversion efficiency of 25%, electricity generation potential in 1997, 2005 and 2010 is 8.34, 9.24 and 9.85 TWh, respectively. The corresponding forecasts of annual electricity requirement are 4.20, 10.50 and 15.60 TWh respectively; thus the energy potential of non-plantation biomass resources in 1997, 2005 and 2010 amounts to 198%, 88% and 63% of the corresponding total electricity demands in the country.

In 1997, the total supply of energy by petroleum fuel was 106.23 PJ. The final energy consumption of petroleum in industrial, household and commercial and transport sectors was 31.62, 3.47 and 55.04 PJ respectively. Therefore, the total annual energy potential of biomass exceeds the energy supplied by fossil fuels in the country.

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