Comparative Analysis of Fuels for Cooking: Life Cycle Environmental Impacts and Economic and Social Considerations

Appendix A: Detailed Environmental, Economic and Social Technical Analyses

December 2016

Submitted to:

Global Alliance for Clean Cookstoves
1750 Pennsylvania Avenue, NW, Suite 300

Submitted by:

Eastern Research Group, Inc. (ERG)
4200 Somerset Drive, Suite 132

Washington, DC 20006

Prairie Village, KS 66208

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

A.1 Introduction

This appendix presents supporting data and information to the *Comparative Analysis of Fuels for Cooking: An Assessment of Environmental, Economic and Social Impacts*. Appendix B describes methodology considerations, process descriptions for each fuel life cycle, and data sources used within the study. Complete citations for data sources used within the study are presented in Appendix C.

To extend the utility of the data and information generated through this study, an initial version of a web-based tool was also developed. The Fuel Analysis, Comparison & Integration Tool (FACIT) provides interactive access to the data and information discussed in this appendix. FACIT allows users to analyze and compare trade-offs of different fuels used to provide energy for cooking. Stakeholders involved in making decisions related to optimizing fuel production, processing, distribution and use should find this tool particularly useful.

The remaining sections present the supporting data and include detailed tables and figures supplemented with country-by-country discussion of these results. The life cycle assessment (LCA) results for fuels are separated by production, distribution and use for all fuels.

Asia

A.2 Detailed Results for China

A.2.1 Overview of China

In China, with the largest population in the world, just over half of the population lives in cities.[1] It is the only Alliance focus country where less than 50 percent of the population uses biomass (wood and crop residues) as a cooking fuel, mostly in rural areas for both cooking and heating, often using the same device. As is common for most developing countries, Chinese households own more than one stove that may use a variety of fuel types. The diversity of geographical regions and fuel options in results in distribution and availability barriers.

China has demonstrated its concern about health, environment, and clean energy by promoting initiatives such as the ethanol program of the early 2000's directed at transportation fuel[2,3] and its use of subsidies and low-interest loans to encourage biogas use for cooking in rural areas.[4,5] In March 2016, China's National People's Congress will pass the 13th Five Year Plan that will create a set of targets and guidelines spanning a range of social, economic, and a particular focus on environmental issues that would limit coal consumption and focus on green, low-carbon development and energy conservation.[6] China has also shown an overall trend of an approximately 2 percent increase in forest land per year in recent years.[7] This increase is the result of ambitious large-scale afforestation programs reported between 2000 and 2010.[8]

The following sub-sections address the environmental, economic, and social considerations related to cooking fuels and stoves for China in greater detail.

A.2.2 Environmental Indicators for China

This section covers the detailed China LCA results for the ten environmental indicators assessed for each fuel. The stove thermal efficiency by fuel and the fuel heating values employed in this study to calculate the LCA results are provided in Table A-1 and Table A-2, respectively. The remainder of this section presents results for each environmental indicator.

Table A-1. Stove Thermal Efficiencies Applied by Fuel Type for China

Fuel Type	Stove Thermal Efficiency	Sources
Firewood	16.3%-19.2%	Zhang, et al. 2000
Crop Residue	10.3%-17.2%	Zhang et al., 2000
Charcoal Briquettes from Wood	17.5%	Singh et al., 2014
Charcoal Briquettes from Bamboo	17.5%	Singh et al., 2014
Non-Carbonized Briquettes from Sawdust	29.9%	GACC, 2015a Urban Uganda, 2015
Non-Carbonized Briquettes from Crop Residues	31.0%	GACC, 2015a
Wood Pellets	53.0%	Jetter et al., 2012
Wood Chips	31.0%	GACC, 2015a
Ethanol from Sugarcane	53.0%	Aprovecho Research Center, 2009
Ethanol from Wood	53.0%	Aprovecho Research Center, 2009
Biogas from Dung	55.0%	Singh et al., 2014
LPG	42.1%-45.2%	Zhang et al., 2000
Kerosene	44.8%-45.9%	Singh et al., 2014
Natural Gas	53.7%-60.9%	Zhang et al., 2000
DME	46.0%	Zhang et al., 2000
Hard Coal	27.2%-37.1%	Zhang et al., 2000
Electricity	67.0%	Aprovecho Research Center, 2006

Table A-2. Fuel Heating Values for China

Fuel Type	**HHV (MJ/kg)**	**Sources**
Firewood	15.3	Zhang et al., 2000
Crop Residue	14.0-14.5	Zhang et al., 2000
Charcoal Briquettes from Wood	27.86	Singh et al., 2014
Charcoal Briquettes from Bamboo	32.19	Singh et al., 2014 NMBA, 2005
Non-Carbonized Briquettes from Sawdust	18.6	Kaur et al., 2012 Grover et al., 1996 Davies et al., 2013 Vyas et al., 2015
Non-Carbonized Briquettes from Crop Residues	15.15	Zhang et al., 2000 Vyas et al., 2015
Wood Pellets	15.9	Jungbluth et al., 2007
Wood Chips	15.3	Zhang et al., 2000
Ethanol from Sugarcane	28.3	Aprovecho Research Center, 2009
Ethanol from Wood	28.3	Aprovecho Research Center, 2009
Biogas from Dung	18.2	Singh et al., 2014
LPG	49.0	Zhang et al., 2000
Kerosene	48.97	Singh et al., 2014
Natural Gas	51.3	Zhang et al., 2000
DME	28.4	Zhang et al., 2000
Hard Coal	13.9	Zhang et al., 2000

A.2.2.1 Total Energy Demand

Table A-3 and Figure A-1 display the total energy demand impact results for fuels in China by life cycle stage. Total energy demand sources consist of non-renewable fuels (natural gas, petroleum, coal, and nuclear) and "renewable" fuels (e.g., biomass, hydro). Energy demand tracks all energy inputs across the life cycle of the fuel, with energy impacts shown at the point of use of the relevant fuel. Due to the complexity of the number of fuels used in the China average electricity grid (79% coal, 14% hydro, 1.8% natural gas, 1.8% nuclear, 1.5% wind, 0.7% biomass, 0.2% oil, 0.2% waste, and 0.1% solar PV per IEA statistics 2012), all total energy demand impacts for electricity are displayed in the use phase.

The total energy demand results are largely a function of the fuel heating value and thermal efficiency of the fuel and stove combination (Table A-2 and Table A-1). Stoves with higher efficiencies (e.g., LPG, kerosene, biogas, ethanol, natural gas, DME, and wood pellets) have a lower total energy demand overall, because more of the heating value of the fuel is converted into useful cooking energy and therefore less fuel must be produced, transported, and burned to deliver the same amount of cooking energy.

A number of observations can be made regarding energy results for the various types of fuels. For sugarcane ethanol, the feedstock energy results include not only the energy value of the sugar that is converted to ethanol but also the energy content of the bagasse, which provides the majority of energy used to process the sugarcane to molasses and then to ethanol. Wood ethanol energy demand impacts are lower than sugarcane since the wood residues are directly converted to ethanol; whereas, the sugarcane ethanol undergoes more agricultural and pre-processing steps to manufacture the ethanol end product. A co-benefit of ethanol production is the production of electricity, which may be exported. As discussed in the Appendix B methodology, this model employs the cut-off allocation methodology; therefore, a credit is not given here to the sugarcane or wood ethanol for exported electricity, so the energy demand impacts for ethanol should be considered as the upper bounds for these fuel types.

For wood fuels and unprocessed crop residues, the wood pellets and wood chips have a lower total energy demand than traditional wood or crop residues. Wood chips and wood pellets typically have a lower moisture content, greater energy content, and greater surface area than the traditional solid biomass, which allows the fuel to combust more efficiently. It is also more common to see improved cookstoves, which have higher stove thermal efficiencies, used in combination with the wood chips and wood pellets in China. Crop residues, consisting of wheat straw, rice straw, and maize straw in China have a comparably lower heating value than wood-based fuels leading to relatively lower total energy demand impacts for crop residue fuels.

For briquettes, the energy demand impact for the carbonized briquettes from wood and bamboo is relatively high compared to other fuels due to the lower stove efficiencies for charcoal briquette stoves in China and the charcoal kiln energy impacts. That is, additional energy is consumed when burning firewood at the kiln to produce charcoal prior to charcoal briquette utilization in a cookstove. Similarly, in processing the commercially made non-carbonized sawdust briquettes, sawdust is combusted to remove the moisture content of the briquettes, which results in the slightly higher total energy demand of the sawdust briquettes compared to other non-carbonized processed biomass fuels. As discussed in Appendix B, it is assumed that 90% of sawdust briquettes in China are produced commercially.

Overall, liquid and gas fuels, which include piped natural gas and biogas, as well as processed solid biomass fuels that do not require additional combustion of solid fuel for processing (e.g., wood pellets) are the fuels that show the lowest overall total energy demand impacts. Hard coal shows the highest overall total energy demand due to the energy required for coal mining and distribution and the low coal stove thermal efficiency. While DME is produced from coal feedstock via gasification, slightly lower total energy demand impacts are seen for DME as compared to coal due to its ability to be transported in lighter weight bottles and its application in more efficient gas stoves.

Table A-3. Total Energy Demand (MJ) for Cooking Fuel Types (China)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed solid biomass	Firewood	0	0	0	32,391	32,391
	Crop residue	0	0	0	39,159	39,159
Processed solid biomass	Charcoal briquettes from wood	0	23,868	0.78	28,308	52,177
	Charcoal briquettes from bamboo	0	27,733	0.78	28,308	56,042
	Non-carbonized briquettes from sawdust	0	35,624	1.71	16,568	52,194
	Non-carbonized briquettes from crop residues	0	516	0.012	15,122	15,638
	Wood pellets	0	2,967	120	9,347	12,434
	Wood chips	0	171	0.011	14,168	14,339
Liquid/gas	Ethanol from sugarcane	485	22,305	181	9,347	32,318
	Ethanol from wood	0	3,201	0.13	9,347	12,548
	Biogas from dung	0	0	0	9,014	9,014
	LPG	1,379	974	91.0	11,349	13,794
	Kerosene	3,537	24.8	91.8	10,924	14,577
	Natural Gas	304	24.4	1,596	8,226	10,150
	DME	17,566	50.7	3,295	10,769	31,681
Other	Hard coal	21,318	4,270	3,252	15,409	44,249
	Electricity	0	0	0	30,023	30,023

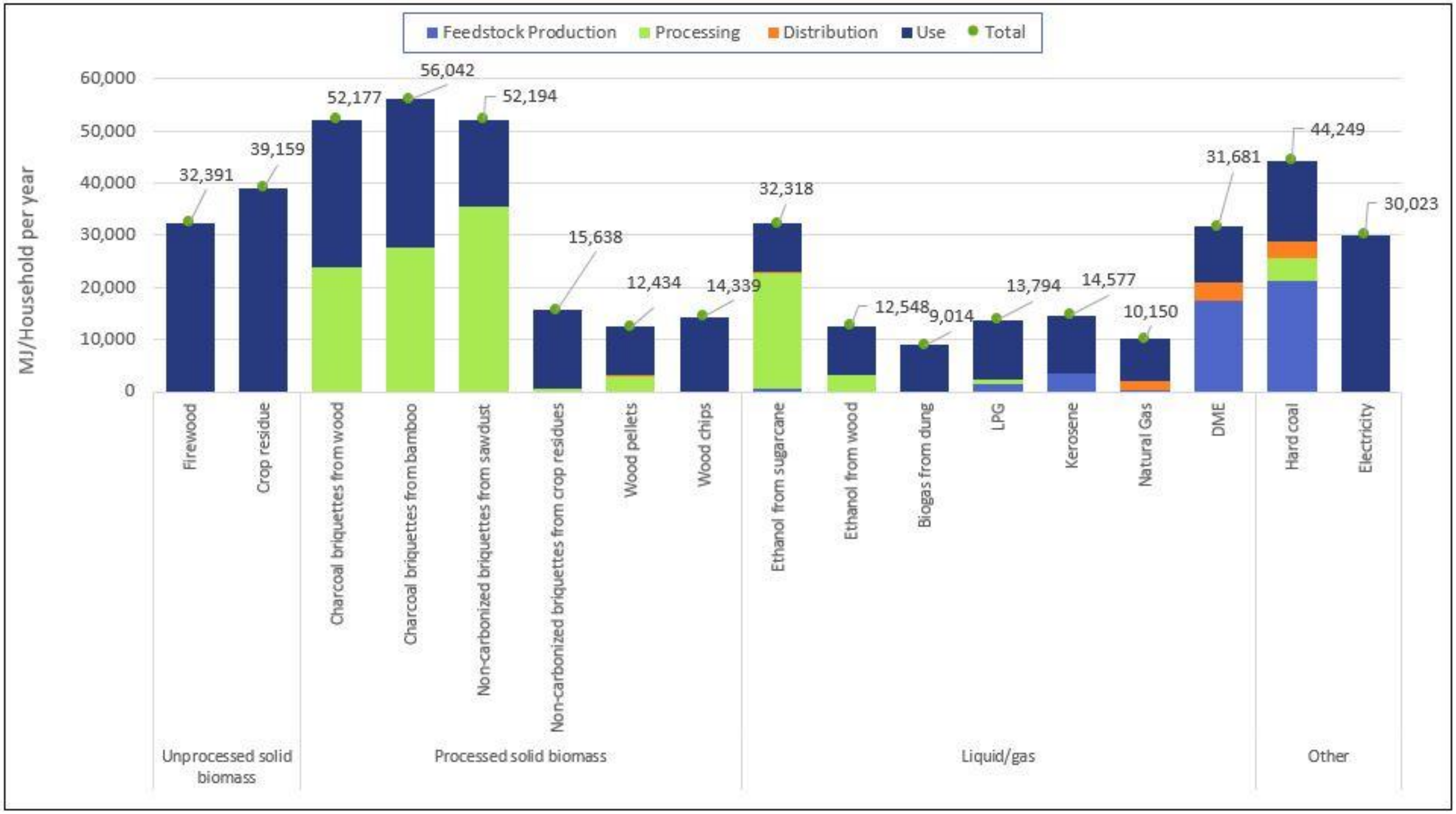


Figure A-1. Total Energy Demand (MJ) for Cooking Fuel Types (China)
To produce, distribute and use cooking fuels by a single household per year

A.2.2.2 Net Energy Demand

Table A-4 and Figure A-2 illustrate the net energy demand impact results for fuels in China by life cycle stage. Net energy demand is calculated in the same way as total energy demand, with the final energy delivered to the cooking pot deducted from the results. The net energy indicator is, therefore, the additional energy required for the life cycle of the cookstove fuel beyond what is delivered to the consumer for cooking purposes. For China, 13.6 MJ of cooking energy are consumed per household per day, which equates to 4,954 MJ per household per year.[9] Utilization of unprocessed solid biomass consumes 5.4 to 6.9 times more energy than is provided to the pot, as listed in the last column of Table A-4. Similar levels of net energy demand are seen for hard coal, DME, electricity and ethanol from sugarcane. The highest net energy demand in China is realized for carbonized briquettes and non-carbonized briquettes from sawdust, which utilize biomass energy in the processing life cycle stage. The lowest overall net energy demand is calculated for non-carbonized briquettes from crop residues, wood pellets, wood chips, ethanol from wood, biogas from dung, LPG, natural gas and kerosene. Production, processing, distribution, and use of these less energy intensive fuels uses 0.82 to 2.16 times the amount of energy delivered to the pot.

Table A-4. Net Energy Demand (MJ) Impacts by Fuel for China

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage					
		Feedstock Production	Processing	Distribution	Use	Total	Net Energy Consumed: Delivered Energy
Unprocessed solid biomass	Firewood	0	0	0	27,437	27,437	5.54
	Crop residue	0	0	0	34,205	34,205	6.90
Processed solid biomass	Charcoal briquettes from wood	0	23,868	0.78	23,354	47,223	9.53
	Charcoal briquettes from bamboo	0	27,733	0.78	23,354	51,088	10.30
	Non-carbonized briquettes from sawdust	0	35,624	1.71	11,614	47,240	9.54
	Non-carbonized briquettes from crop residues	0	516	0.012	10,168	10,685	2.16
	Wood pellets	0	2,967	120	4,393	7,480	1.51
	Wood chips	0	171	0.011	9,215	9,385	1.89
Liquid/gas	Ethanol from sugarcane	485	22,305	181	4,393	27,364	5.52
	Ethanol from wood	0	3,201	0.13	4,393	7,594	1.53
	Biogas from dung	0	0	0	4,061	4,061	0.82
	LPG	1,379	974	91.0	6,395	8,840	1.78
	Kerosene	3,537	24.8	91.8	5,970	9,623	1.94
	Natural Gas	304	24.4	1,596	3,272	5,196	1.05
	DME	17,566	50.7	3,295	5,815	26,727	5.40
Other	Hard coal	21,318	4,270	3,252	10,455	39,295	7.93
	Electricity	0	0	0	25,069	25,069	5.06

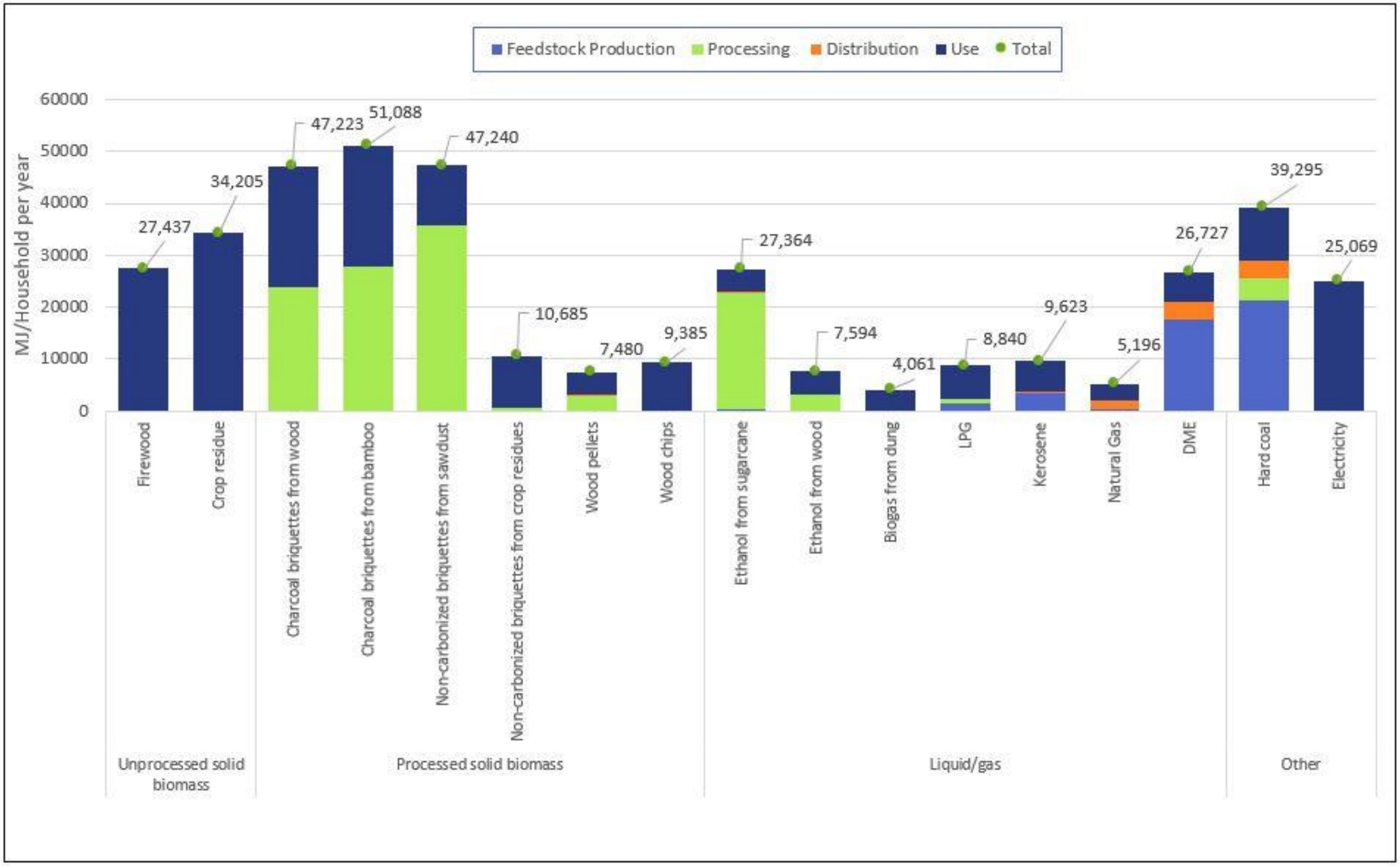


Figure A-2. Net Energy Demand (MJ) for Cooking Fuel Types (China)
To produce, distribute and use cooking fuels by a single household per year

A.2.2.3 Global Climate Change Potential (100a)

Table A-5 and Figure A-3 present the global climate change potential (GCCP) impact results for fuels in China by life cycle stage. The GCCP impact category represents the heat trapping capacity of greenhouse gases over a 100 year time horizon. Fossil fuel GCCP impacts are dominated by combustion emissions in the cookstove use stage. Coal has the highest impacts, since it is derived from non-renewable carbon and the thermal efficiency of coal stoves (27.2%-37.1%) is relatively low compared to the other fossil fuel options (e.g., natural gas stove efficiency is 44.8%-45.9%) (Table A-1). Coal is widely used and transported long distances in China, resulting in a notable contribution of GHGs from the distribution life cycle stage. Electricity in China is derived primarily from coal (79%) and hydroelectric facilities (14.8%), which is the primary reason its impacts are similar but slightly lower than coal.[10] For consistency with other fuels, the fuel combustion emissions associated with electricity generation have been allocated to the use stage here, although electricity-related fuel combustion emissions do not occur at the household level. Biogas GCCP impacts are primarily from methane leakage during the production of biogas in an anaerobic digester. Sugarcane ethanol, crop residue (unprocessed residues and crop residues briquettes), and charcoal briquettes from bamboo are derived from renewable biomass that removed CO_2 from the atmosphere during growth; therefore, the CO_2 emissions released from combustion of these fuels is considered carbon neutral, as discussed in detail in the Appendix B methodology. Impacts for these renewable fuels during the use phase are driven by nitrous oxide and methane emissions during cookstove use. Impacts associated with fertilizer production and emissions from application also play a role in the sugarcane ethanol overall impacts.

Based on the trend in forest area in China and the annual generation of biomass per hectare, 57% of the firewood required for cooking can be sustainably sourced; therefore, the combustion emissions for the non-renewable 43% of wood are not considered carbon-neutral. This adjustment is also applied to other wood fuels (wood-derived charcoal briquettes, wood pellets and wood chips), but not to fuels derived from wood wastes (wood ethanol and non-carbonized briquettes from sawdust). With the cut-off modeling methodology used in this analysis, wood wastes are treated as a “free” product (all burdens are allocated to the primary wood product, e.g., lumber, which is outside the scope of this study), so emissions of biomass CO_2 for fuels derived from wood waste are treated as carbon neutral. For charcoal briquettes, GCCP impacts for carbonization of the wood in the kiln are comparable in magnitude to the emissions from combustion of the charcoal briquettes in a cookstove. Charcoal kiln impacts are largely driven by the methane emissions during the carbonization process. Combustion emissions for bamboo-derived charcoal briquettes are lower than for wood-derived charcoal briquettes because bamboo is a renewable biomass crop so all combustion emissions are considered carbon-neutral, while only 57% of the wood combustion emissions (for the renewable percentage of the wood supply) are considered carbon-neutral.

Table A-5. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (China)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total
		Feedstock Production	Processing	Distribution	Use	
Unprocessed Solid Biomass	Firewood	0	0	0	1,390	1,390
	Crop Residue	0	0	0	271	271
Processed Solid Biomass	Charcoal Briquettes from Wood	0	1,385	57.5	1,381	2,824
	Charcoal Briquettes from Bamboo	0	1,211	57.5	227	1,496
	Non-Carbonized Briquettes from Sawdust	0	81.6	126	56.2	264
	Non-Carbonized Briquettes from Crop Residues	0	86.9	0.88	110	198
	Wood Pellets	0	212	8.15	729	949
	Wood Chips	0	13.6	0.80	739	754
Liquid/Gas	Ethanol from Sugarcane	395	26.2	13.0	4.74	439
	Ethanol from Wood	0	25.9	9.75	4.74	40.4
	Biogas from Dung	0	45.5	0	6.57	52.1
	LPG	112	6.70	94.5	717	930
	Kerosene	165	62.5	6.45	793	1,027
	Natural Gas	46.2	149	134	727	1,056
	DME	732	188	336	456	1,711
Other	Hard Coal	358	76.0	1,664	1,787	3,885
	Electricity	0	0	0	2,458	2,458

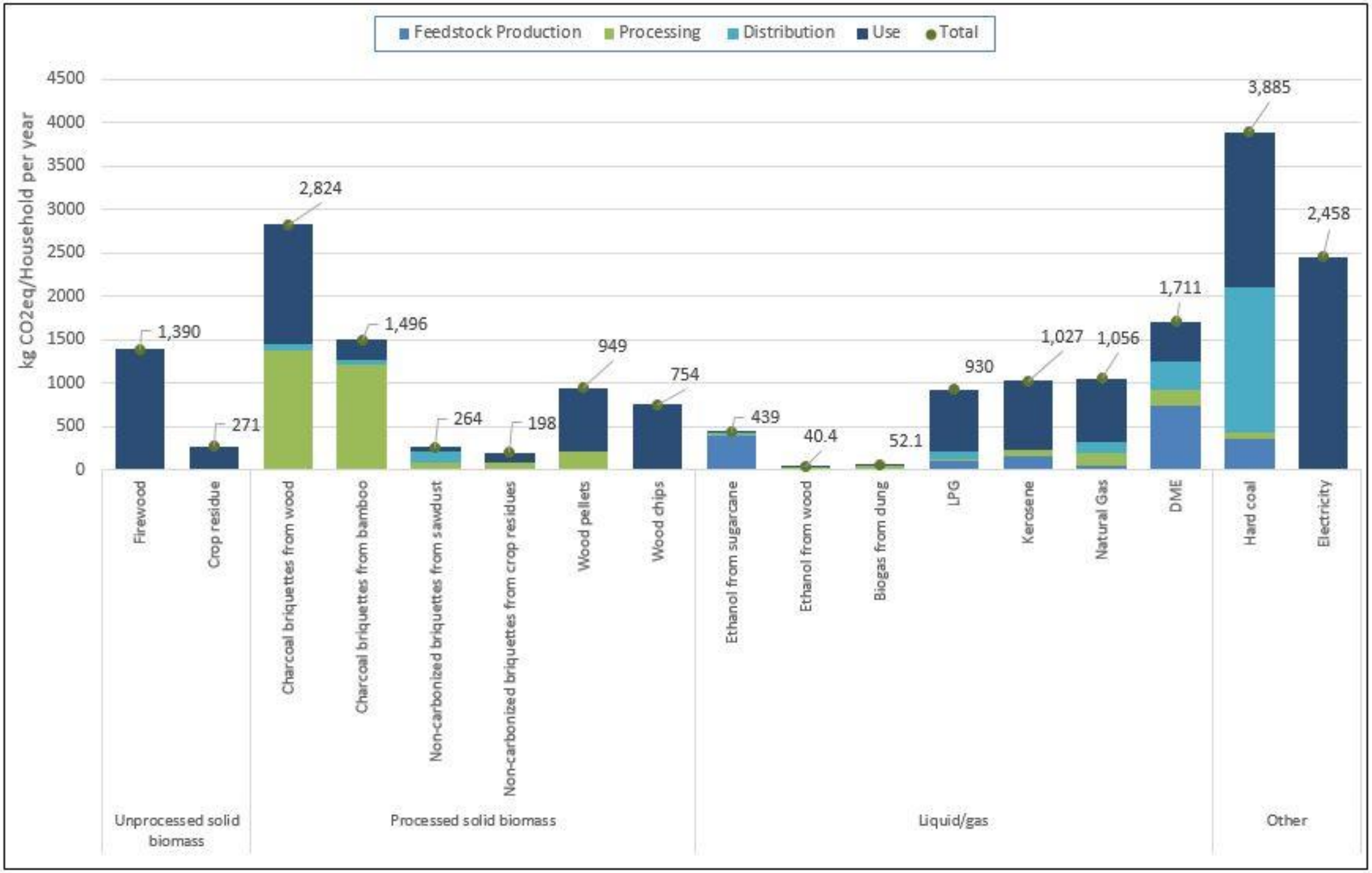


Figure A-3. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (China)
To produce, distribute and use cooking fuels by a single household per year

A.2.2.4 Black Carbon and Short-Lived Climate Pollutants

Table A-6 and Figure A-4 display the black carbon and short-lived climate pollutants impact results for fuels in China by life cycle stage. Black carbon (BC) is formed by incomplete combustion of fossil and bio-based fuels. BC is the carbon component of particulate matter (PM) with aerodynamic diameter less than or equal to 2.5 microns (PM2.5). This is the size of PM that most strongly absorbs light and thus has potential radiative forcing effects (i.e., potential to contribute to global warming). Potential climate forcing impacts resulting from BC emissions include direct, albedo (i.e., fraction of solar energy hitting the earth that is reflected), and other effects. BC is emitted with other particles (e.g., organic carbon) and criteria pollutants such as nitrogen and sulfur dioxides. Though some of these co-pollutants may exert a cooling effect on climate, the net effects of BC emissions likely contribute to global climate warming. Appendix B shows the 20 year global warming potential and black carbon equivalent values used in the results calculation. Results are presented here based on BC equivalents. The highest BC impacts are seen for charcoal briquettes produced in a traditional earth mound kiln, a processing method associated with high particulate matter. However, charcoal briquettes are not a commonly used cookstove fuel type in China. Utilization of the liquid and gas fuels result in the lowest overall BC impacts. Some life cycle stages have negative BC equivalent impacts, which is the case when emissions of SO_x and organic carbon (pollutants with net cooling effects on the climate) are greater than the emissions of BC and other co-emitted pollutants that lead to short term warming impacts. This is the case for certain life cycle stages of coal as well as electricity derived from coal. Coal, a material with a notable sulfur content, leads to high levels of sulfur dioxide combustion emissions.

Table A-6. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (China)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	1.48	1.48
	Crop Residue	0	0	0	3.43	3.43
Processed Solid Biomass	Charcoal Briquettes from Wood	0	19.9	0.0082	1.27	21.2
	Charcoal Briquettes from Bamboo	0	3.04	0.0082	1.27	4.32
	Non-Carbonized Briquettes from Sawdust	0	0.14	0.0085	0.48	0.63
	Non-Carbonized Briquettes from Crop Residues	0	-0.021	5.9E-05	0.73	0.71
	Wood Pellets	0	-0.052	7.1E-04	0.10	0.053
	Wood Chips	0	0.0032	5.3E-05	1.08	1.09
Liquid/Gas	Ethanol from Sugarcane	-0.0086	-0.036	-0.0070	0.014	-0.038
	Ethanol from Wood	0	0.0081	0.0014	0.014	0.023
	Biogas from Dung	0	0	0	0.034	0.034
	LPG	0.014	-0.094	-0.030	0.023	-0.087
	Kerosene	-0.15	-0.023	-0.0011	0.011	-0.16
	Natural Gas	-0.018	2.5E-04	-3.6E-04	0.0074	-0.011
	DME	-0.15	0.43	-0.0034	-0.011	0.27
Other	Hard Coal	-0.024	0.20	0.090	-0.036	0.23
	Electricity	0	0	0	-0.60	-0.60

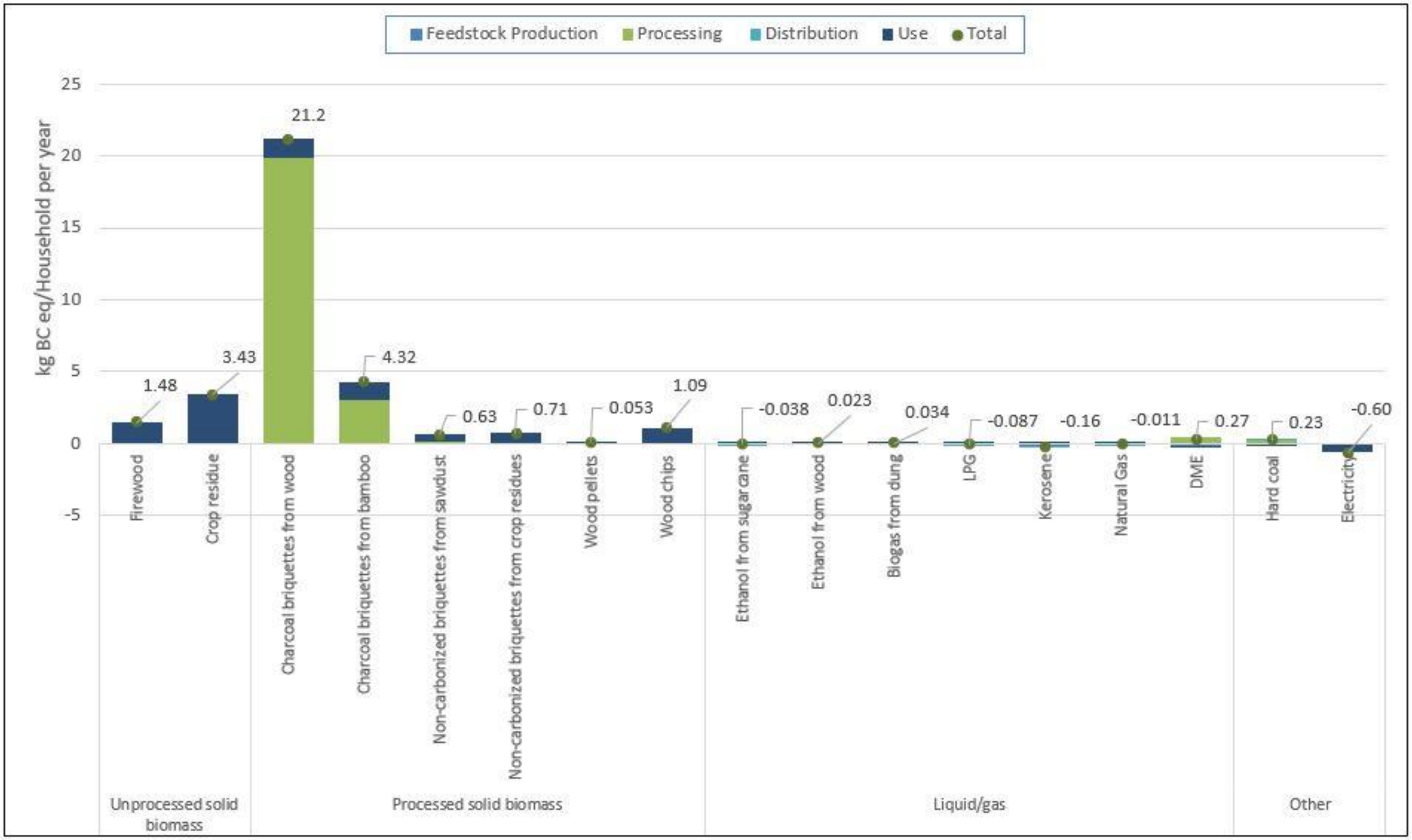


Figure A-4. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (China)
To produce, distribute and use cooking fuels by a single household per year

A.2.2.5 Particulate Matter Formation Potential

Table A-7 and Figure A-5 show the particulate matter formation impact results for fuels in China by life cycle stage. Particulate matter can contribute to many negative health impacts such as effects on breathing and respiratory systems, damage to lung tissue, cancer, and premature death. Primary and secondary pollutants leading to particulate matter formation as well as PM2.5 are characterized here to kg PM10 eq. Traditional biomass fuels and charcoal briquettes, scarcely utilized cooking fuels in China, lead to the greatest particulate matter formation impacts. For charcoal, the carbonization of the wood in the kiln dominates the overall life cycle impacts. Charcoal from bamboo has slightly lower particulate matter impacts than wood charcoal. This is because a larger portion of bamboo charcoal is estimated to be produced in brick kilns; whereas, all wood charcoal in China is assumed to be produced in traditional earth mound kilns. Commercial non-carbonized sawdust briquettes are also a fuel with one of the highest particulate matter impacts due to particulate matter formation pollutants from the processing stage, for combusting a portion of the briquette output to dry the briquettes. Advanced liquid fuels as well as biogas, natural gas and wood pellets have comparably small particulate matter impacts. Most of the particulate matter impacts for electricity are derived from the coal mix in the average China electrical grid. The particulate matter impacts from fuel combustion for electricity generation have been allocated to the use phase, although the actual particulate matter emissions for electricity do not occur at the household level. Particulate matter impacts for DME, derived from coal gasification, are associated with coal production in the feedstock stage.

Table A-7 Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (China)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	7.36	7.36
	Crop Residue	0	0	0	16.9	16.9
Processed Solid Biomass	Charcoal Briquettes from Wood	0	93.0	0.18	3.45	96.6
	Charcoal Briquettes from Bamboo	0	9.98	0.18	3.45	13.6
	Non-Carbonized Briquettes from Sawdust	0	26.9	0.22	2.09	29.2
	Non-Carbonized Briquettes from Crop Residues	0	0.23	0.0015	3.01	3.25
	Wood Pellets	0	0.57	0.020	0.51	1.10
	Wood Chips	0	0.052	0.0014	4.59	4.65
Liquid/Gas	Ethanol from Sugarcane	0.56	0.17	0.094	0.0021	0.83
	Ethanol from Wood	0	0.95	0.054	0.0067	1.01
	Biogas from Dung	0	0	0	0.38	0.38
	LPG	0.79	0.018	0.015	0.16	0.98
	Kerosene	1.04	0.0054	0.021	0.088	1.15
	Natural Gas	0.096	0.0034	0.088	0.095	0.28
	DME	3.29	0.034	0.18	0.23	3.73
Other	Hard Coal	0.87	1.25	0.71	0.53	3.37
	Electricity	0	0	0	6.61	6.61

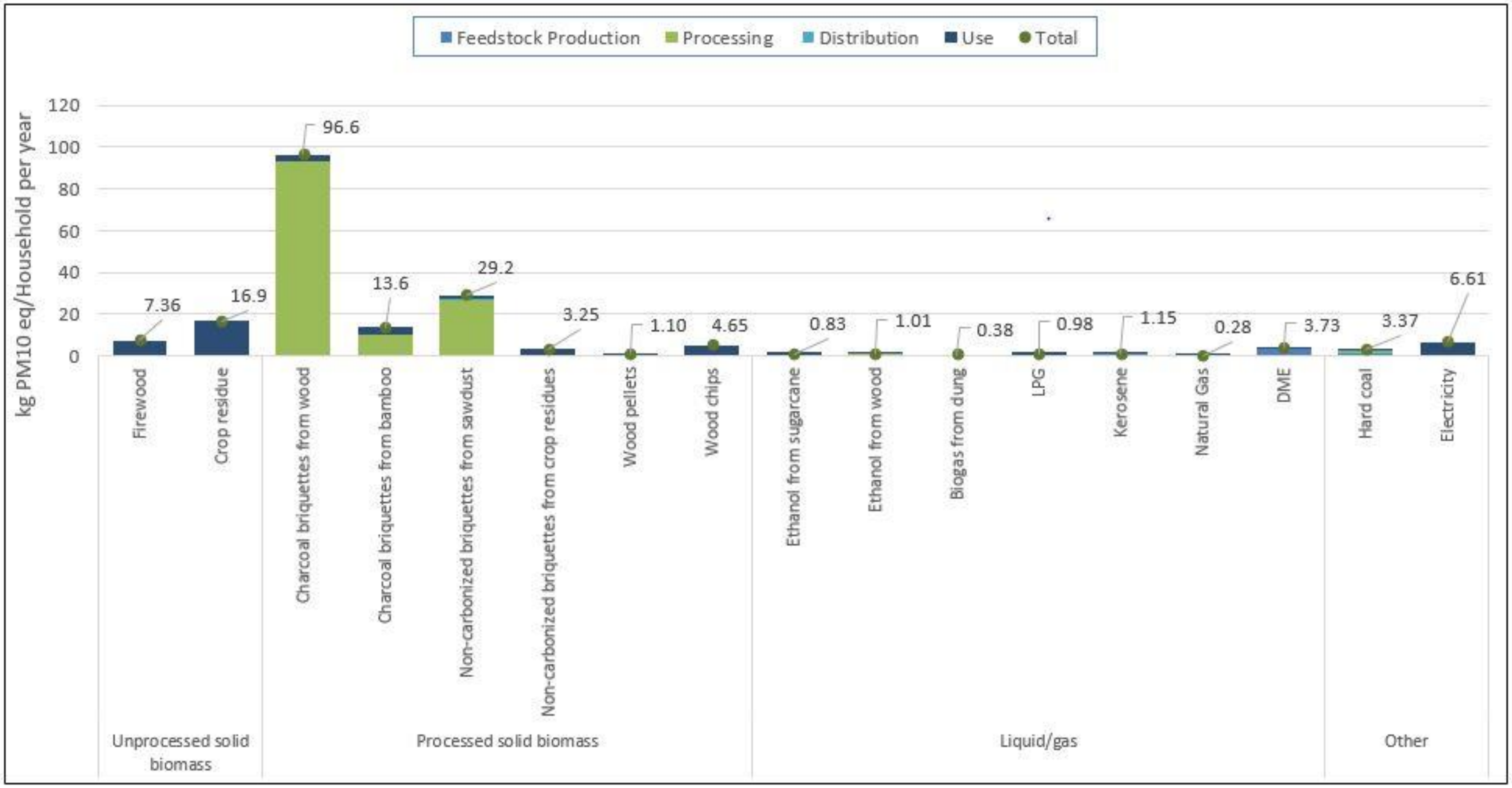


Figure A-5. Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (China)
To produce, distribute and use cooking fuels by a single household per year

A.2.2.6 Fossil Fuel Depletion

Table A-8 and Figure A-6 provide the fossil fuel depletion impact results for fuels in China by life cycle stage. Fossil depletion captures the consumption of fossil fuels, primarily coal, natural gas, and crude oil. All fuels are normalized to kg oil eq based on the heating value of the fossil fuel relative to the heating value of a kg of oil. The fossil depletion associated with traditional biomass fuels as well as biogas and ethanol from wood is negligible, as these fuels are not derived from fossil fuel, and collection of these fuels is done manually. While biomass fuels are not derived from fossil fuels, some fossil fuels may be consumed across the life cycle of these fuels for energy inputs to fuel production and processing, distribution, and disposal. Fossil depletion for wood pellets is associated with electricity usage for pelletization and some transport, while sugarcane ethanol fossil depletion is primarily from fertilizers during cane production, as well as diesel for farm operation and distribution of the feedstock and fuel. Some fossil depletion impacts are also seen for processing the wood chips and non-carbonized briquettes for the portions of these fuels that are not processed manually (as discussed in detail in Appendix B, 90% of non-carbonized and carbonized wood/bamboo briquetting is modeled as mechanized in China, and 100% of wood chipping is modeled as mechanized in China). Fossil depletion impacts are highest for coal, LPG, natural gas, kerosene and electricity, as these sources of energy are largely or entirely derived from fossil fuels. The greatest impacts are seen for coal. Although coal has a lower kg oil eq per MJ extracted compared to crude oil or natural gas due to its lower heating value, the lower coal stove thermal efficiencies (27-37%) compared to the more efficient gas stoves (54-61%, as shown in Table A-1) leads to this relatively high fossil depletion for the coal stove scenario.

Table A-8. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (China)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed solid biomass	Firewood	0	0	0	0.012	0.012
	Crop residue	0	0	0	0.076	0.076
Processed solid biomass	Charcoal briquettes from wood	0	0.92	0.019	0.030	0.97
	Charcoal briquettes from bamboo	0	0.99	0.019	0.077	1.09
	Non-carbonized briquettes from sawdust	0	12.3	0.041	0.012	12.4
	Non-carbonized briquettes from crop residues	0	16.9	2.8E-04	0.0028	16.9
	Wood pellets	0	41.1	0.15	8.9E-04	41.2
	Wood chips	0	4.07	2.6E-04	0.0040	4.07
Liquid/gas	Ethanol from sugarcane	60.3	13.8	4.29	0	78.5
	Ethanol from wood	0	2.61	0.0032	0	2.62
	Biogas from dung	0	0	0	0	0
	LPG	31.9	22.5	2.11	262	319
	Kerosene	81.3	0.57	2.11	251	335
	Natural Gas	7.23	0.58	37.9	195	241
	DME	305	0.88	57.2	187	550
Other	Hard coal	377	75.4	57.5	272	782
	Electricity	0	0	0	474	474

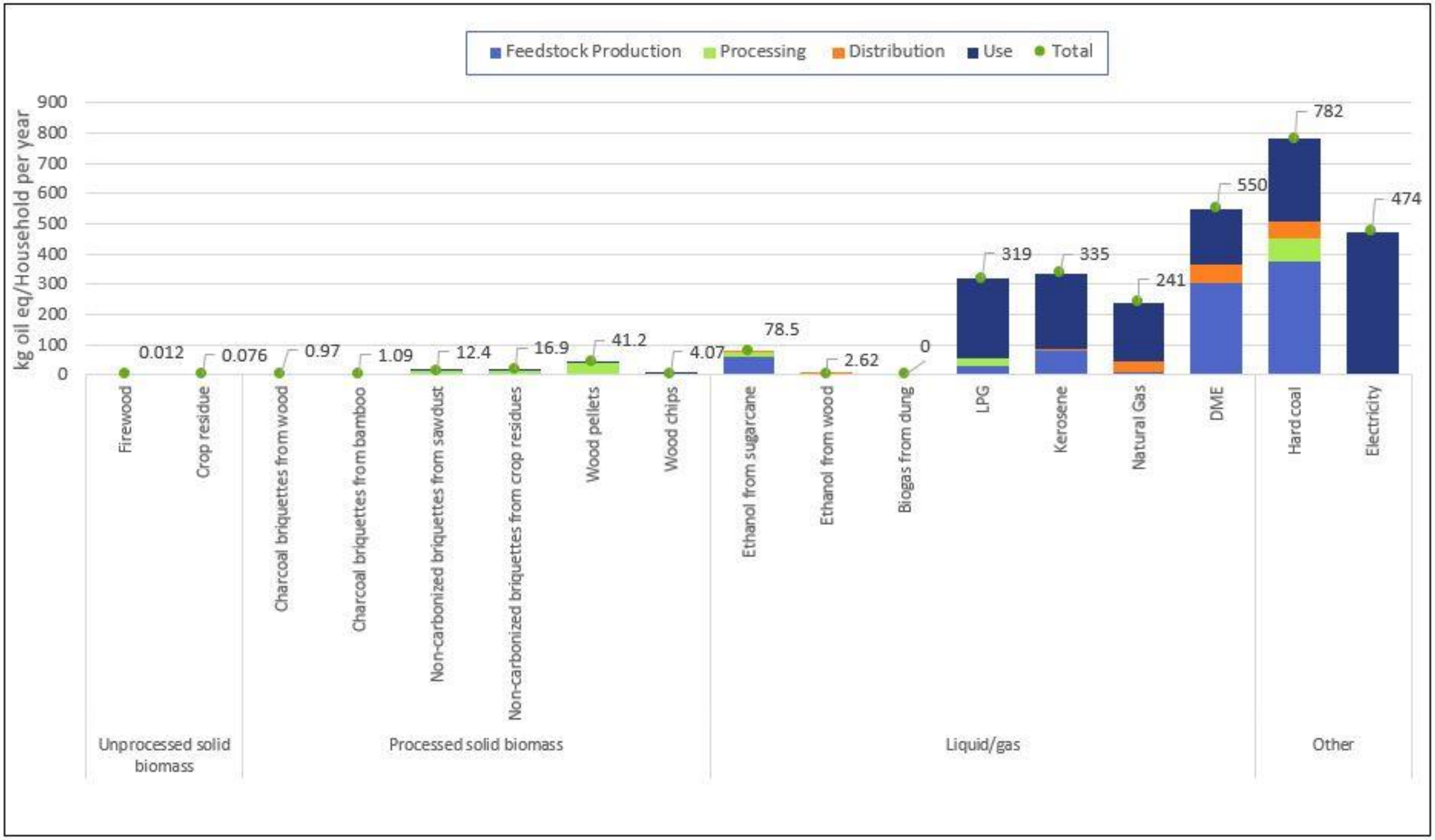


Figure A-6. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (China)
To produce, distribute and use cooking fuels by a single household per year

A.2.2.7 Water Depletion

Table A-9 and Figure A-7 illustrate the water depletion impact results for fuels in China by life cycle stage. Water depletion results are based on the volume of fresh water inputs over the life cycle of the assessed fuels. Water may be incorporated in the fuel product, evaporated, or returned to the same or different water body or to land. If the water is returned to the same water body, it is assumed the water is returned at a degraded quality, and therefore is considered consumptive use. Water consumption includes evaporative losses from establishment of hydroelectric dams but does not include the water passing through the turbine, since that water is not removed from its source. The hydropower in the electricity mix (source of 14.8% of electricity in China)[11] drives the overall water depletion impacts for electricity. In this case, for simplicity, electricity impacts have been allocated to the use life cycle stage. Water depletion associated with wood pellets and biomass briquettes is also due to electricity usage during pelletization/briquetting. Water depletion impacts are also notable for sugarcane ethanol, as irrigation is required for the cane production. Some water depletion impacts are also seen for the biogas to maintain the digester, but these are negligible when compared to the evaporative losses from hydropower in the electricity grid. Water depletion impacts are negligible for the traditional biomass fuels, which are not irrigated. Because the water content of these fuels comes from the atmosphere as rainfall, the water released back to the atmosphere when the biomass is dried or combusted is not considered consumptive use.

Table A-9. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (China)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	0.093	0.093
	Crop Residue	0	0	0	0.58	0.58
Processed Solid Biomass	Charcoal Briquettes from Wood	0	5.65	1.8E-04	0.23	5.88
	Charcoal Briquettes from Bamboo	0	5.47	1.8E-04	0.23	5.70
	Non-Carbonized Briquettes from Sawdust	0	74.8	3.9E-04	0.091	74.9
	Non-Carbonized Briquettes from Crop Residues	0	103	2.7E-06	0.022	103
	Wood Pellets	0	251	23.3	0.0044	275
	Wood Chips	0	4.21	2.5E-06	0.031	4.24
Liquid/Gas	Ethanol from Sugarcane	274	66.3	2.53	0	343
	Ethanol from Wood	0	23.3	3.0E-05	0	23.3
	Biogas from Dung	0	5.16	0	0	5.16
	LPG	267	7.97	7.74	0	283
	Kerosene	34.7	315	8.70	0	358
	Natural Gas	17.3	0.97	10.3	0	28.6
	DME	101	15.0	20.3	0	136
Other	Hard Coal	47.4	55.9	242	33.1	378
	Electricity	0	0	0	2,598	2,598

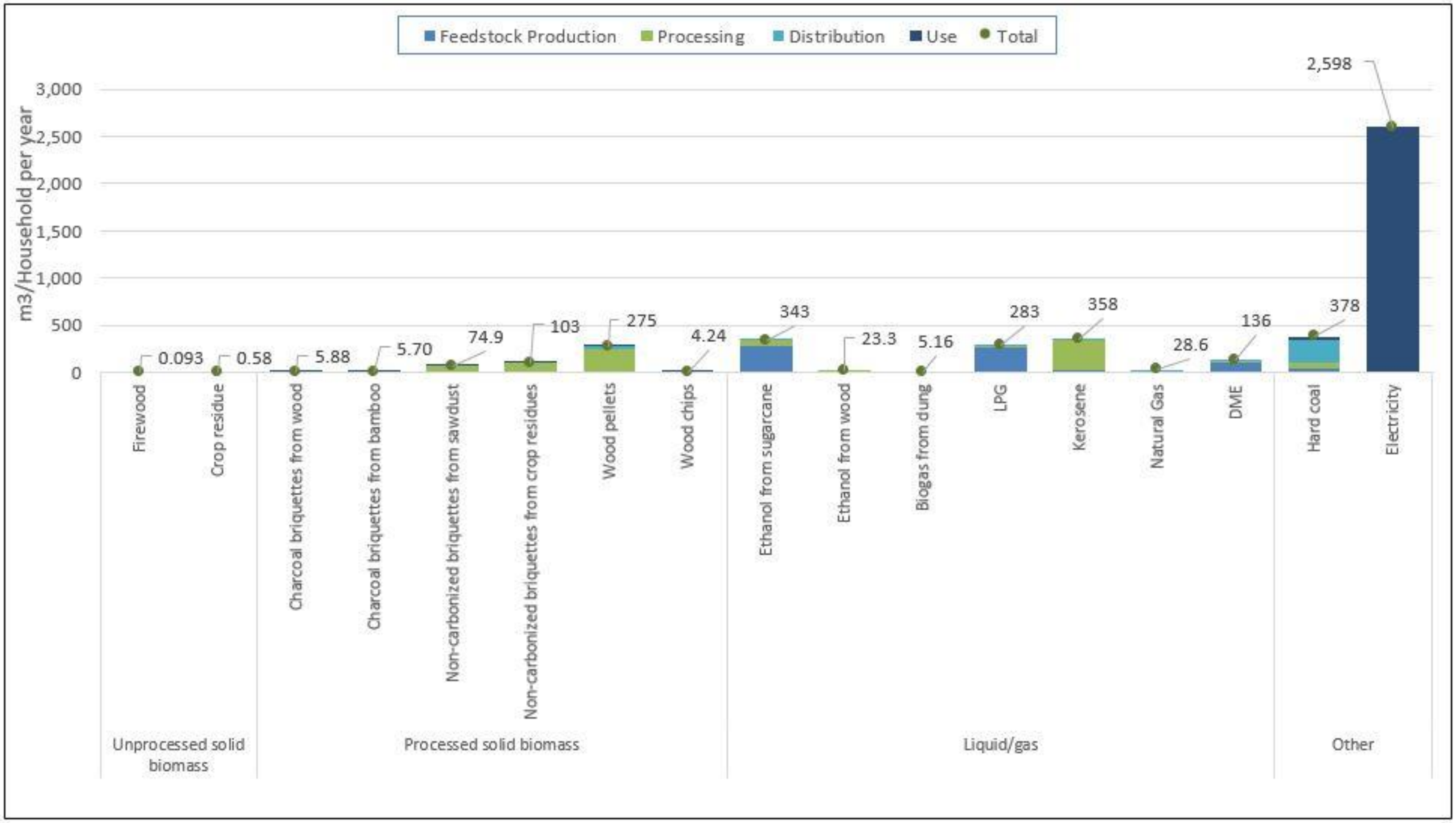


Figure A-7. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (China)
To produce, distribute and use cooking fuels by a single household per year

A.2.2.8 Terrestrial Acidification Potential

Table A-10 and Figure A-8 show the terrestrial acidification potential impact results for fuels in China by life cycle stage. Terrestrial acidification quantifies the acidifying effect of substances on their environment. Important contributing emissions include SO_2, NO_x, and NH_3. Acidification impacts are dominated by coal usage, either as a direct fuel or as an input to electricity generation, and as feedstock for DME. Electricity usage for pelletization drive biomass pellet acidification impacts. Sulfur dioxide emissions from coal are notably higher than sulfur dioxide emissions from combustion of other fuels. Ethanol contains no sulfur, so there are no sulfur dioxide emissions, a main cause of acidification, for the ethanol cookstove use stage. No NO_x emissions data for ethanol combustion in a cookstove were available, although qualitative reports stated that ethanol combustion leads to minimal nitrogen oxide emissions. The lowest overall acidification impacts are seen for natural gas, ethanol from wood, and biogas. Because land applied digested sludge from biogas production is used by another product system, it is considered to be outside the system boundaries for this analysis; however, it is possible that this land applied digested sludge could lead to emissions of ammonia, an acidifying substance.

Table A-10 Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (China)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	1.43	1.43
	Crop Residue	0	0	0	1.49	1.49
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.062	0.42	1.01	1.50
	Charcoal Briquettes from Bamboo	0	0.056	0.55	1.01	1.62
	Non-Carbonized Briquettes from Sawdust	0	0.63	0.53	0.28	1.44
	Non-Carbonized Briquettes from Crop Residues	0	0.75	0.0037	0.38	1.13
	Wood Pellets	0	1.81	0.045	0.17	2.02
	Wood Chips	0	0.10	0.0033	0.47	0.58
Liquid/Gas	Ethanol from Sugarcane	1.52	0.75	0.30	0	2.57
	Ethanol from Wood	0	0.53	0.071	0	0.61
	Biogas from Dung	0	0	0	0.53	0.53
	LPG	3.06	0.058	0.036	0.23	3.38
	Kerosene	4.07	0.017	0.062	0.15	4.30
	Natural Gas	0.41	0.0070	0.25	0.18	0.84
	DME	4.61	0.11	0.49	0.66	5.86
Other	Hard Coal	3.92	0.67	1.73	1.60	7.92
	Electricity	0	0	0	21.2	21.2

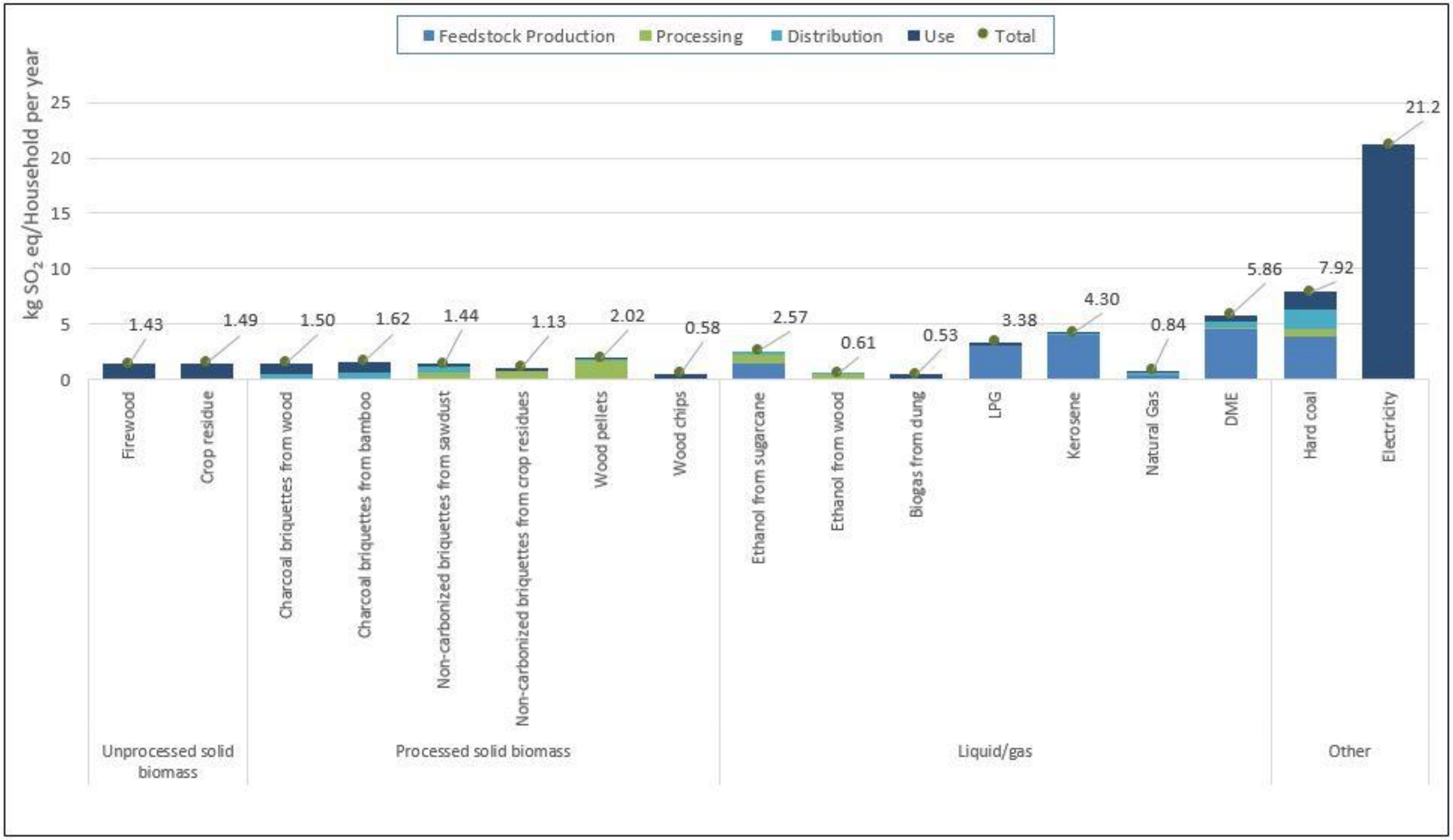


Figure A-8. Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (China)
To produce, distribute and use cooking fuels by a single household per year

A.2.2.9 Freshwater Eutrophication Potential

Table A-11 and Figure A-9 provide the freshwater eutrophication potential impact results for fuels in China by life cycle stage. Eutrophication assesses the impacts from excessive load of macro-nutrients to the environment and eventual deposition in freshwater, which can result in algal blooms, oxygen depletion, and fish kills. Pollutants contributing to this category are all P based (e.g. phosphate, phosphoric acid, phosphorus). Traditional fuels (firewood and crop residues) and charcoal briquettes result in the highest eutrophication potential impacts. This is due to the much larger ash quantity produced from these fuel types compared to all other fuels. The ash from the firewood (used in its raw form or to produce charcoal briquettes) and from the crop residues, which contains phosphorus, is assumed to be land applied, which leads to soil emissions and eventual runoff into freshwater. Waterborne emissions of phosphorus are also notable for coal production, including the coal feedstock production utilized in the electricity grid and for gasification to DME. While impacts are comparably smaller for ethanol, there are some eutrophication impacts occurring from use of phosphorus-based fertilizer in sugarcane production. There are no eutrophication impacts associated with biogas. Application of the digested sludge from the biogas system would likely lead to some eutrophication impacts, but utilization of this useful co-product is outside the system boundaries of this study. The digested sludge impacts are allocated to the product system it serves (i.e. nutrients for crop production). Impacts from fossil based fuels and biomass pellets are minimal compared to the traditional fuels and charcoal briquettes. The non-carbonized processed biomass fuels have slightly lower eutrophication potential impacts than traditional unprocessed biomass fuels. Because processed biomass burns more efficiently than unprocessed biomass, less fuel must be burned, leading to an overall lower quantity of ash produced.

Table A-11. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (China)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	0.30	0.30
	Crop Residue	0	0	0	1.88	1.88
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.63	2.1E-07	0.75	1.38
	Charcoal Briquettes from Bamboo	0	0.063	2.1E-07	0.75	0.81
	Non-Carbonized Briquettes from Sawdust	0	0.10	4.5E-07	0.29	0.40
	Non-Carbonized Briquettes from Crop Residues	0	0.011	3.1E-09	0.071	0.082
	Wood Pellets	0	0.027	0.0024	0.014	0.043
	Wood Chips	0	5.9E-04	2.8E-09	0.10	0.10
Liquid/Gas	Ethanol from Sugarcane	0.16	0.011	3.5E-04	5.3E-06	0.17
	Ethanol from Wood	0	0.023	3.5E-08	5.3E-06	0.023
	Biogas from Dung	0	0	0	0	0
	LPG	0.038	8.4E-04	6.0E-04	0	0.040
	Kerosene	0.050	2.5E-04	0.0010	0	0.051
	Natural Gas	0.0015	1.1E-04	0.0018	0	0.0034
	DME	0.31	0.0016	0.0036	0	0.31
Other	Hard Coal	0.39	0.020	0.028	0.0042	0.44
	Electricity	0	0	0	0.31	0.31

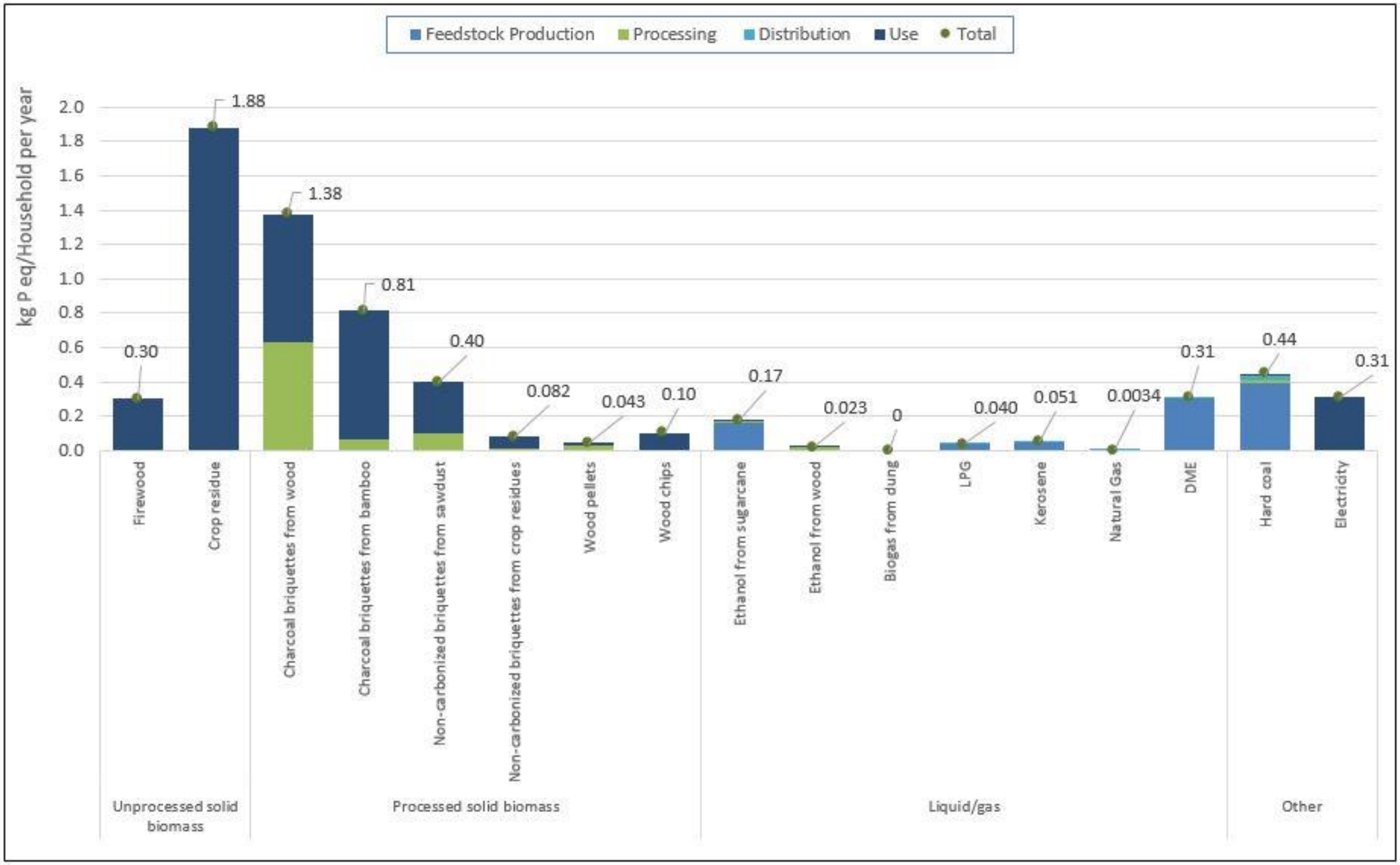


Figure A-9. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (China)
To produce, distribute and use cooking fuels by a single household per year

A.2.2.10 Photochemical Oxidant Formation Potential

Table A-12 and Figure A- present the photochemical oxidant formation potential impact results for fuels in China by life cycle stage. The photochemical oxidant formation (i.e., smog formation) results are an indicator of the potential for formation of reactive substances that cause harm to human health and vegetation. Results are characterized here to kg of non-methane volatile organic compounds (NMVOC) eq. Some key emissions for cookstove fuel systems that contribute to photochemical oxidant formation include carbon monoxide, methane, nitrogen oxides, NMVOCs, and sulfur dioxide. Traditional biomass fuels and charcoal briquettes lead to the greatest photochemical formation impacts, with charcoal briquettes from bamboo having the highest overall impacts. For charcoal briquettes, impacts are split between the fuel processing stage (carbonization in a kiln) and the use stage. Higher emissions of NMVOCs were documented for the brick kilns used to produce bamboo charcoal briquettes compared to the earth mound kilns used for wood charcoal briquettes, leading to the overall higher photochemical oxidant formation seen for bamboo charcoal briquettes relative to charcoal briquettes from wood. Photochemical oxidant impacts for electricity are primarily associated with utilization of hard coal in the grid mix. Impacts from fuel combustion emissions for electricity generation have been allocated to the use stage here for simplicity, but impacts do not occur at the household level. Photochemical oxidant formation impacts are relatively small for the liquid fuels, processed non-carbonized biomass, natural gas, and biogas.

Table A-12. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (China)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	8.96	8.96
	Crop Residue	0	0	0	12.5	12.5
Processed Solid Biomass	Charcoal Briquettes from Wood	0	26.3	0.73	24.9	51.9
	Charcoal Briquettes from Bamboo	0	94.7	0.73	24.9	120
	Non-Carbonized Briquettes from Sawdust	0	1.34	0.90	3.37	5.61
	Non-Carbonized Briquettes from Crop Residues	0	0.33	0.0063	5.16	5.49
	Wood Pellets	0	0.80	0.067	0.51	1.37
	Wood Chips	0	0.18	0.0057	9.59	9.77
Liquid/Gas	Ethanol from Sugarcane	0.84	0.23	0.23	0.31	1.61
	Ethanol from Wood	0	0.094	0.12	0.31	0.53
	Biogas from Dung	0	0.018	0	0.54	0.56
	LPG	1.33	0.026	0.086	0.54	1.98
	Kerosene	1.69	0.010	0.044	0.36	2.10
	Natural Gas	0.38	0.0038	0.40	0.33	1.12
	DME	0.86	0.050	8.58	0.47	9.97
Other	Hard Coal	0.88	0.35	2.76	1.95	5.94
	Electricity	0	0	0	9.26	9.26

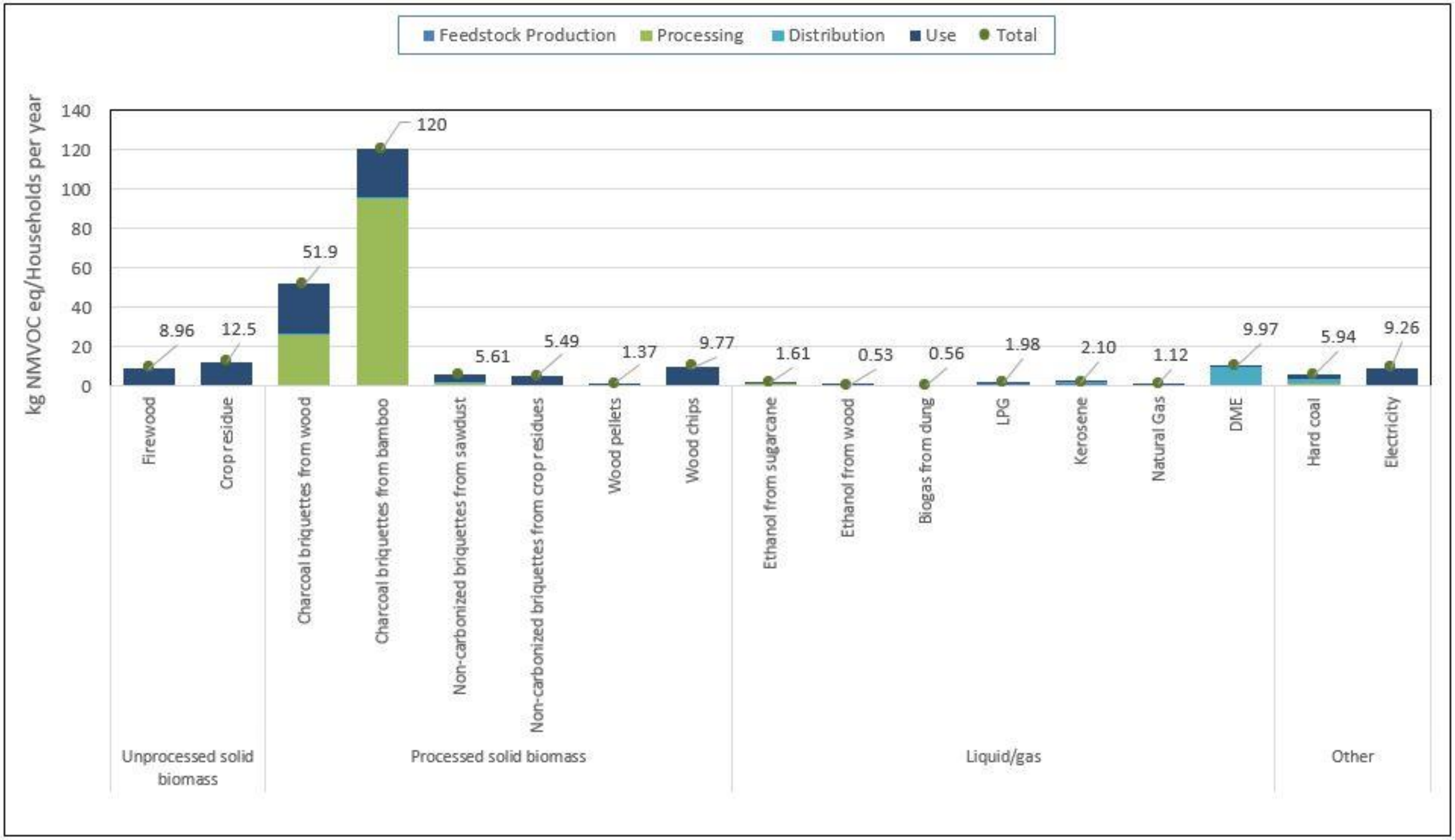


Figure A-10. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (China)
To produce, distribute and use cooking fuels by a single household per year

A.2.3 Economic Indicators for China

A.2.3.1 Fuel Use

Figure A- shows the percentages of the population in China using various types of fuel as their primary cooking fuel. Fuel use is divided fairly evenly among three main fuels, with LPG, coal, and biomass each used as the primary cooking fuel by about 30 percent of the population. Just over 10 percent of the population uses electricity. [12] China is unique among the Phase 1 countries in its high use of coal and electricity for cooking.

Other fuels, such as kerosene, biogas, charcoal briquettes, and dung cakes are used by a relatively small percentage of the population.[13,14] There is no reported use of ethanol or bamboo charcoal briquettes for cooking.[15] Ethanol is commonly used in China as a transportation fuel. Bamboo, if used for cooking, is normally burned in unprocessed form.

LPG, natural gas, coal gas, electricity, and biomass pellets are primarily available in urban areas. In rural areas, fuels such as coal, firewood, non-carbonized briquettes and biogas systems are more common. [16] No data breaking out urban and rural use of cooking fuels were found for China.

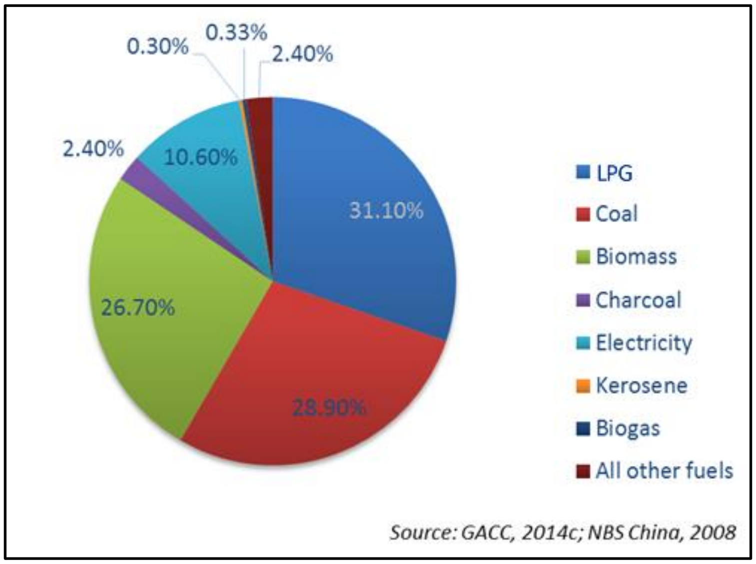


Figure A-11. Current Cooking Fuel Mix in China

A.2.3.2 Fuel Imports, Exports, Production, and Demand in China

Table A-13 shows the levels of imports, exports, production, and demand (assumed to be equal to current consumption) of several fuels in China. The data on total and household demand do not differentiate between fuel use for cooking and fuel use for other purposes such as heating. The table shows that China is essentially self-sufficient in its LPG production, with domestic production meeting nearly all of its demand. [17] Nearly 75 percent of LPG demand is by households. Similarly, most of China's charcoal demand is met through domestic production,[18] but charcoal is not often used for cooking in China,[19,20] so this is likely used for manufacturing, construction or other purposes.

China's ethanol production, at 7 billion liters,[21] is the highest of the Phase 1 countries. About 35 percent of this is used in beverages, with the remaining 65 percent used for ethanol for fuel and other industrial chemicals,[22] and little to no use as a cooking fuel.[23] In China, ethanol is currently manufactured predominantly from grains (mostly corn and wheat) rather than from the sugarcane or sawdust feedstocks that are in the scope of this report, although the government has been promoting other non-food grain feedstocks, so this may change in the future.[24] Trade in ethanol is low in China largely due to government policies, including a ban on using imported fuel ethanol in the transportation sector. A trial importation of ethanol to study the economics and trading channels for ethanol was carried out in 2014, so ethanol trade to and from China could increase in the future.[25]

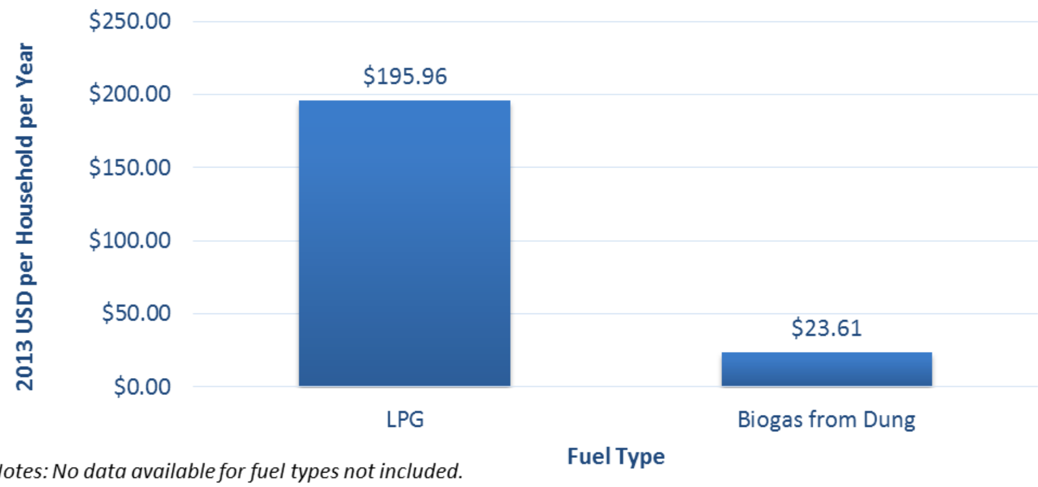
China's production of firewood is relatively high, at 178.8 million tonnes in 2013,[26] but this number may only capture firewood that is formally traded but not wood gathered by the end user for cooking purposes. Production of wood pellets is relatively insubstantial compared to the leading fuels. Of the 100,000 tonnes of wood pellets produced, 90,000 tonnes are consumed domestically. Production of wood chips is relatively high, at 39.4 million tonnes, supplemented by another 9.2 million tonnes that are imported, but there is no data on how much of this is consumed in China.[27,28]

Table A-13. Fuel Imports, Exports, Production, and Demand in China (Tonnes per Year)

Fuel	Imports	Exports	Production	Demand		Sources
				Total	Household	
LPG	3,495,600	1,190,900	21,263,400	21,759,700	16,071,500	UNSD, 2011
Ethanol	171	1,383	5,565,195	553,585	No data	UNSD, 2013 OECD/FAO, 2014
Firewood	5,110	48	178,830,986	No data	No data	UNSD, 2013 FAO, 2014
Charcoal Briquettes	233,340	52,329	1,715,504	1,896,515	No data	UNSD, 2011
Wood Pellets	No data	3,293	100,000	90,000	No data	UNSD, 2013 FAO, 2014 IEA Bioenergy, 2011
Wood Chips	9,157,137	69	39,355,000	No data	No data	UNSD, 2013 FAO, 2014

A.2.3.3 Fuel Cost in China

Figure A-12 shows the price per household per year for the cooking fuels in China for which data are available. LPG is by far the most expensive fuel, at about $196 per household per year,[29] although this might be offset to some extent by local government subsidies based on income level.[30] The annualized cost of the digesters used to produce biogas from animal dung or crop residue is approximately $24 per year.[31,32] In general, fuel prices tend to be higher in rural than urban areas.[33]



Notes: No data available for fuel types not included.
Mainali et al. (2012) estimate does not specify biogas feedstock, used to estimate biogas from animal dung.

Sources: Christiaensen, 2012; Mainali et al, 2012

Figure A-12. Fuel Cost Indicator for Cooking Fuels in China

A.2.4 Social Indicators for China

A.2.4.1 Government Policies/Programs

Due in part to large-scale afforestation programs reported between 2000 and 2010, China has shown an overall trend of approximately two percent increase in forest land per year over recent years.[34] These improvements, however, have not led to complacency and the Chinese government remains vigilant about deforestation. As such, the government has promoted fuels such as wood pellets and non-carbonized wood briquettes (larger pellets) that use the country's biomass supplies more efficiently.[35] As of 2014, 58 percent of biomass pellet and briquette producers used government subsidies, with those subsidies covering between 5 and 60 percent of production costs. In addition to providing subsidies aimed at helping producers scale their operations in a highly competitive and fragmented market, the government also provides distribution assistance for 26 percent of biomass pellet and briquette producers and manufacturers. Despite these interventions, 9 percent of pellet and briquette producers maintain they need more government support to overcome key market constraints.[36]

In addition to nontraditional fuels derived from wood, the Chinese government has also promoted the use of ethanol. China's 12th Five Year Plan (2011-2015) set goals for increasing biomass and biofuel production—including the development of cellulosic ethanol—and as of 2014, China has seven plants licensed for fuel ethanol production.[37] These plants use a variety of feedstocks, though corn (76 percent of total production) and wheat (14 percent) are the most common. Cassava (8 percent), sweet sorghum (less than 1 percent) and corn cobs (1 percent), currently represent small shares of China's ethanol feedstock portfolio, but the government has actively encouraged their use since 2008 so corn and wheat are not diverted from food supplies. Cassava and sweet sorghum, however, still compete with food grains for arable land.[38]Although government subsidies for fuel ethanol predate the shift away from food-grain feedstocks, the use of subsidies in the mid-2000s suggests the government's willingness to provide incentives focused on the adoption of ethanol.[39]

The government has also supported a variety of initiatives to promote biogas use in domestic settings within rural areas. In addition to the central government's ten-year effort to support the production of biogas from crop residues,[40] some provincial governments provide subsidies or low-interest loans to help supply rural household with biogas digesters using animal dung.[41]

A.2.4.2 Supply & Access Challenges

Fuels assessed in this study for which data are available fall into three broad categories: 1) fuels that are available but are used for purposes other than cooking, 2) fuels that have some distribution, but only in certain environments (e.g., peri-urban and affluent rural areas), and 3) fuels that have widespread uptake and are reliably available in rural areas. The primary fuel in the first category is ethanol. China is producing ethanol in substantial quantities, but it is used primarily for biofuel in the transportation sector and not for cooking.[42] In the second category is LPG. Approximately 20 years ago there was a boom in LPG use in cities, but since then, use has transitioned to peri-urban environments and wealthy rural settings.[43] Given this shift, it seems reasonable to conclude that LPG is more reliably acquired in these new locations.

Biogas from crop residue[44] and biogas from animal dung fall into the final category: fuels that have widespread adoption and can be acquired reliably in rural environments.[45,46] Unlike other fuels, where feedstock availability might be a key concern, reliability of acquisition for biogas pertains more to the presence of distribution and technical support networks. The widespread adoption of both forms of biogas systems indicate that such networks are available: China has over 38.51 million households using crop residue biogas systems[47] and 3.5 million using animal dung biogas systems.[48] With strong governmental support, China's implementation of household biogas is "continuously ranked first in the world and has the widest scope and most extensive impacts."[49] Naturally, these impacts are most pronounced in rural environments where ample feedstocks are available. For example, municipalities without substantial farming sectors, such as Beijing, Shanghai, and Tianjin, have far fewer biogas systems.[50]

A.2.4.3 Distribution & Adoption Challenges

The primary challenge facing the distribution of alternative fuels in China is the displacement of coal. Coal is popular, widely available, and cheap, making it difficult for nontraditional fuels to gain market share.[51] In rural areas where firewood and agricultural residues are more commonly used for cooking, the displacement of coal tends to be less challenging but still faces barriers. Due to increasing wage rates for the rural workforce (wages increased by a factor of almost twenty-eight from 1995 to 2010) and a slower rate of increase of coal prices (a factor of sixteen and a quarter over the same time period), the opportunity cost of manually collecting and processing fuel has increased substantially relative to coal prices.[52]

Limited awareness of the benefits of alternative fuels compared to coal is also a key challenge in China. In order to combat this, the successful promotion of alternative fuels will likely require highlighting the potential for energy cost savings and focusing on heads of households who tend to make fuel purchasing decisions. These decision makers are presumably men given that past fuel promotion initiatives have not been marketed towards women and have not emphasized gender-based issues such as women's increased exposure to indoor air pollution while cooking.[53]

Challenges are documented for three fuels: charcoal briquettes from bamboo, biogas from animal dung, and LPG. Although bamboo is available and burned as an unprocessed cooking fuel in some regions of China, it is not currently used for briquettes. The distribution of charcoal briquettes from bamboo would therefore compete with the convenience of burning raw bamboo and would also face the challenge of displacing a number of competing, non-cookfuel uses for bamboo.[54] The primary challenge facing the wide-scale adoption of biogas from animal dung at the household level relates to the shift from individual cultivation of livestock to industrial farming. The rise of industrially-farmed livestock and poultry has led to a reduction in household-level access to the raw materials for biogas digesters.[55] For LPG, the primary concern relates to maintenance of the cylinders: although there are local safety resources available, people perceive such maintenance and licensing procedures as a waste of time and money.[56]

A.2.4.4 Protection & Safety

Chinese households are most likely to adopt nontraditional fuels for cooking when they can use that same fuel for heating. As such, when end-users are considering safety impacts, they often approach the issue with both uses in mind. For example, such households might take into consideration overnight fuel consumption and the increased potential for burns associated with stove operation during non-cooking hours.[57] Collection of animal dung, crop residues, and firewood usually occurs somewhat close to the household, and no safety issues were found in the literature. However, users of biogas systems, for which dung and crop residues are feedstocks, do express concerns about explosions.[58] For purchased fuels considered in this analysis (e.g., LPG or ethanol), no safety issues during the purchase of the fuels were found within the literature.

A.2.4.5 Time & Drudgery

In China, the only fuel for which time savings estimates are available is firewood. Time estimates located in the literature are limited to a specific gender and season: women in rural areas spend between 1.2 and 9.6 hours each week in winter gathering fuel.[59] However, some high level insights are available to put this in perspective. One study found that the opportunity cost of one day of fuelwood gathering is more than twice as high as the cost of five days' worth of coal.[60] With respect to cooking times over firewood in rural China, women spend between 11.9 and 23.9 hours per week in winter compared to between 0.6 and 2.7 hours per week for their male counterparts.[61]

Although corresponding time savings data are not available for other fuels, these findings illustrate that for women who are collecting and cooking over traditional biomass, wood alternatives and fuel efficient cookstoves can reduce their unpaid carework burdens. This leads to increased time for them to complete other responsibilities and can increase gender equality in the household.

A.2.4.6 Income Earning Opportunities

Given the novelty of the feedstock-fuel combinations in the present study, limited information regarding the income earning opportunities associated with specific cooking fuels is available. China is home to established small enterprises that are producing noncarbonized briquettes, chips, and pellets from wood. Opportunities are assumed to be present within these industries despite the lack of available data.[62] More detail is available for distribution opportunities associated with biogas from animal dung. Through state funding, China's household biogas service system has expanded rapidly to include six provincial training bases, 536 county-level service stations, and 64,576 rural service networks. This infrastructure, in conjunction with a workforce of over 300,000 involved with biodigester construction, installation, and follow-up services, suggests the presence of substantial income earning opportunities.[63]

A.2.4.7 Opportunities for Women Along the Value Chain

According to the Global Alliance for Clean Cookstoves 2013 Results Report, the clean cookstove industry in China currently has 8,064 employees (28 percent of whom are women).[64] However, there are currently no data available to estimate potential increases of skills for women with respect to specific fuels. Although women are the primary cooks in China, industry is only beginning to acknowledge the importance of incorporating them into the supply chain.[65]

A.3 Detailed Results for India

A.3.1 Overview of India

India is the second most populous country in the world, with almost 1.3 billion residents; the environmental, economic, and social implications of cooking fuel use therefore have large-scale effects.

Over two-thirds of the population of India still use solid fuels, such as firewood, crop residues, or dung, for cooking.[66] In February 2016, the government announced budget plans to set aside 2,000 crore to meet the initial cost of providing cooking gas connections to every rural household to protect the almost 142 million rural households from the "curse of smoke." [67] Cooking fuel affordability is a key issue, as approximately 33 percent of the Indian population lives below the poverty line, surviving on $1.25 per day.[68]

In 2010, 31 percent of India's population lived in urban areas and 69 percent in rural areas.[69] The mix of cooking fuels used is quite different in each. Rural households have more access than urban households to biomass fuels that are free for the gathering, such as dung, firewood, and crop residues, while processed fuels such as LPG and kerosene are more readily available in urban areas. Access to fuel is also affected by seasonal weather, as rural households may be unable to gather biomass fuels on a regular basis during the monsoon season.

Adequate supply of fuels to sustainably support demand is an important consideration. For example, although India has shown an overall trend of an approximately 2 percent increase in forest land per year in recent years,[70] the increases are not sufficient to meet all of the country's demand for firewood and other wood-derived cooking fuels.

Finally, cultural preferences are an important consideration. For example, there is a strong preference in India for the smell and taste of bread prepared using firewood, while fuel's influence on taste is generally not an issue for foods cooked in water (e.g., lentils, rice, and curries).[71] For homes where the cooking fire serves additional purposes (e.g., providing heat or light), changes to the cooking fuel or type of cookstove would likely require the household to use other fuels for these functions.

The following sub-sections address the environmental, economic, and social considerations related to cooking fuels and stoves for India in greater detail.

A.3.2 Environmental Indicators for India

This section covers the detailed India LCA results for the ten environmental indicators assessed for each fuel. The stove thermal efficiency by fuel and the fuel heating values employed in this study to calculate the LCA results are provided in Table A-14 and Table A-15, respectively. The remainder of this section presents results for each environmental indicator.

Table A-14. Stove Thermal Efficiencies Applied by Fuel Type for India

Fuel Type	Stove Thermal Efficiency	Sources
Firewood	13.5%	Singh et al., 2014
Crop Residue	11.0%	Singh et al., 2014
Dung Cake	8.5%	Singh et al., 2014

Table A-14. Stove Thermal Efficiencies Applied by Fuel Type for India

Fuel Type	Stove Thermal Efficiency	Sources
Charcoal Briquettes from Wood	17.5%	Singh et al., 2014
Charcoal Briquettes from Bamboo	17.5%	Singh et al., 2014
Non-Carbonized Briquettes from Sawdust	25.5%	GACC 2015a Urban Uganda, 2015
Non-Carbonized Briquettes from Crop Residues	31.0%	GACC 2015a
Wood Pellets	53.0%	Jetter et al., 2012
Wood Chips	31.0%	GACC 2015a
Ethanol from Sugarcane	53.0%	Aprovecho Research Center, 2009
Ethanol from Wood	53.0%	Aprovecho Research Center, 2009
Biogas from Dung	55.0%	Singh et al., 2014
LPG	57.0%	Singh et al., 2014
Kerosene	47.0%	Singh et al., 2014
Hard Coal	15.50%	Singh et al., 2014
Electricity	67.0%	Aprovecho Research Center, 2006

Table A-15. Fuel Heating Values for India

Fuel Type	HHV (MJ/kg)	Sources
Firewood	15.84	Singh et al., 2014
Crop Residue	14.62	Singh et al., 2014
Dung Cake	13.25	Singh et al., 2014
Charcoal Briquettes from Wood	27.86	Singh et al., 2014
Charcoal Briquettes from Bamboo	32.19	Singh et al., 2014 NMBA, 2005
Non-Carbonized Briquettes from Sawdust	18.8	Kaur et al., 2012 Vyas et al., 2015
Non-Carbonized Briquettes from Crop Residues	16.84	Vyas et al., 2015
Wood Pellets	17.94	Singh et al., 2014 Jetter et al., 2012
Wood Chips	15.84	Singh et al., 2014
Ethanol from Sugarcane	28.33	Aprovecho Research Center, 2009
Ethanol from Wood	28.33	Aprovecho Research Center, 2009
Biogas from Dung	18.2	Singh et al., 2014
LPG	53.37	Singh et al., 2014
Kerosene	48.97	Singh et al., 2014
Hard Coal	16.30	Singh et al., 2014

A.3.2.1 Total Energy Demand

Table A-16 and Figure A-13 display the total energy demand impact results for fuels in India by life cycle stage. Total energy demand sources consist of non-renewable fuels (natural gas, petroleum, coal, and nuclear) and "renewable" fuels (e.g., biomass, hydro). Energy demand tracks all energy inputs across the life cycle of the fuel, with energy impacts shown at the point of use of the relevant fuel. Due to the complexity of the number of fuels used in the India average electricity grid (71% coal, 11% hydro, 8% natural gas, 3% nuclear, 2.5% wind, 2% oil, 1.7% biofuels, 0.2% solar PV, and 0.09% waste per IEA statistics 2012), all total energy demand impacts for electricity are displayed in the use phase.

The total energy demand results are largely a function of the fuel heating value and thermal efficiency of the fuel and stove combination (Table A-14 and Table A-15). Stoves with higher efficiencies (e.g., LPG, kerosene, biogas, ethanol, and biomass pellets) have a lower total energy demand overall, because more of the heating value of the fuel is converted into useful cooking energy and therefore less fuel must be produced, transported, and burned to deliver the same amount of cooking energy.

A number of observations can be made regarding energy results for the various types of fuels. For sugarcane ethanol, the feedstock energy results include not only the energy value of the sugar that is converted to ethanol but also the energy content of the bagasse, which provides the majority of energy used to process the sugarcane to molasses and then to ethanol. Wood ethanol energy demand impacts are lower than sugarcane since the wood residues are directly converted to ethanol; whereas, the sugarcane ethanol undergoes more agricultural and pre-processing steps to manufacture the ethanol end product. A co-benefit of ethanol production is the production of electricity, which may be exported. As discussed in the Appendix B methodology, this model employs the cut-off allocation methodology; therefore, a credit is not given here to the sugarcane or wood ethanol for exported electricity, so the energy demand impacts for ethanol should be considered as the upper bounds for these fuel types.

For wood fuels and unprocessed crop residues, the wood pellets and wood chips have a lower total energy demand than traditional wood or crop residues. Wood chips and wood pellets typically have a lower moisture content, greater energy content, and greater surface area than the traditional solid biomass, which allows the fuel to combust more efficiently. It is also more common to see improved cookstoves, which have higher stove thermal efficiencies, used in combination with the wood chips and wood pellets in India. Crop residues have a comparably lower heating value than wood-based fuels leading to relatively lower total energy demand impacts for crop residue fuels.

For briquettes, the energy demand impact for the carbonized briquettes from wood and bamboo is relatively high compared to other fuels due to the lower stove efficiencies for metal charcoal briquette stoves in India and the charcoal kiln energy impacts. That is, additional energy is consumed when burning firewood at the kiln to produce charcoal prior to charcoal briquette utilization in a cookstove. Similarly, in processing the commercially made non-carbonized sawdust briquettes, sawdust is combusted to remove the moisture content of the briquettes, which results in the relatively higher total energy demand of the sawdust briquettes compared to other non-carbonized processed biomass fuels.

Overall, liquid and gas fuels as well as processed solid biomass fuels not requiring additional combustion of solid fuel for processing (e.g., wood pellets) lead to the lowest overall total energy demand impacts. Hard coal results in the highest overall total energy demand due to the low coal stove thermal efficiency and the energy required for coal mining and distribution.

Table A-16. Total Energy Demand (MJ) for Cooking Fuel Types (India)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed solid biomass	Firewood	0	0	0	30,981	30,981
	Crop residue	0	0	0	9,670	9,670
	Dung cake	0	0	0	51,628	51,628
Processed solid biomass	Charcoal briquettes from wood	0	18,043	1.57	22,944	40,989
	Charcoal briquettes from bamboo	0	24,758	1.57	22,944	47,704
	Non-carbonized briquettes from sawdust	0	21,363	1.65	15,746	37,110
	Non-carbonized briquettes from crop residues	0	527	0.0050	12,571	13,098
	Wood pellets	0	775	12.3	7,575	8,362
	Wood chips	0	22.1	0.011	12,954	12,976
Liquid/gas	Ethanol from sugarcane	891	17,579	81.5	7,575	26,127
	Ethanol from wood	0	931	0.27	7,575	8,507
	Biogas from dung	0	0	0	7,306	7,306
	LPG	102	250	152	7,348	7,852
	Kerosene	135	374	116	9,749	10,373
Other	Hard coal	29,370	0	43.5	25,903	55,317
	Electricity	0	0	0	21,853	21,853

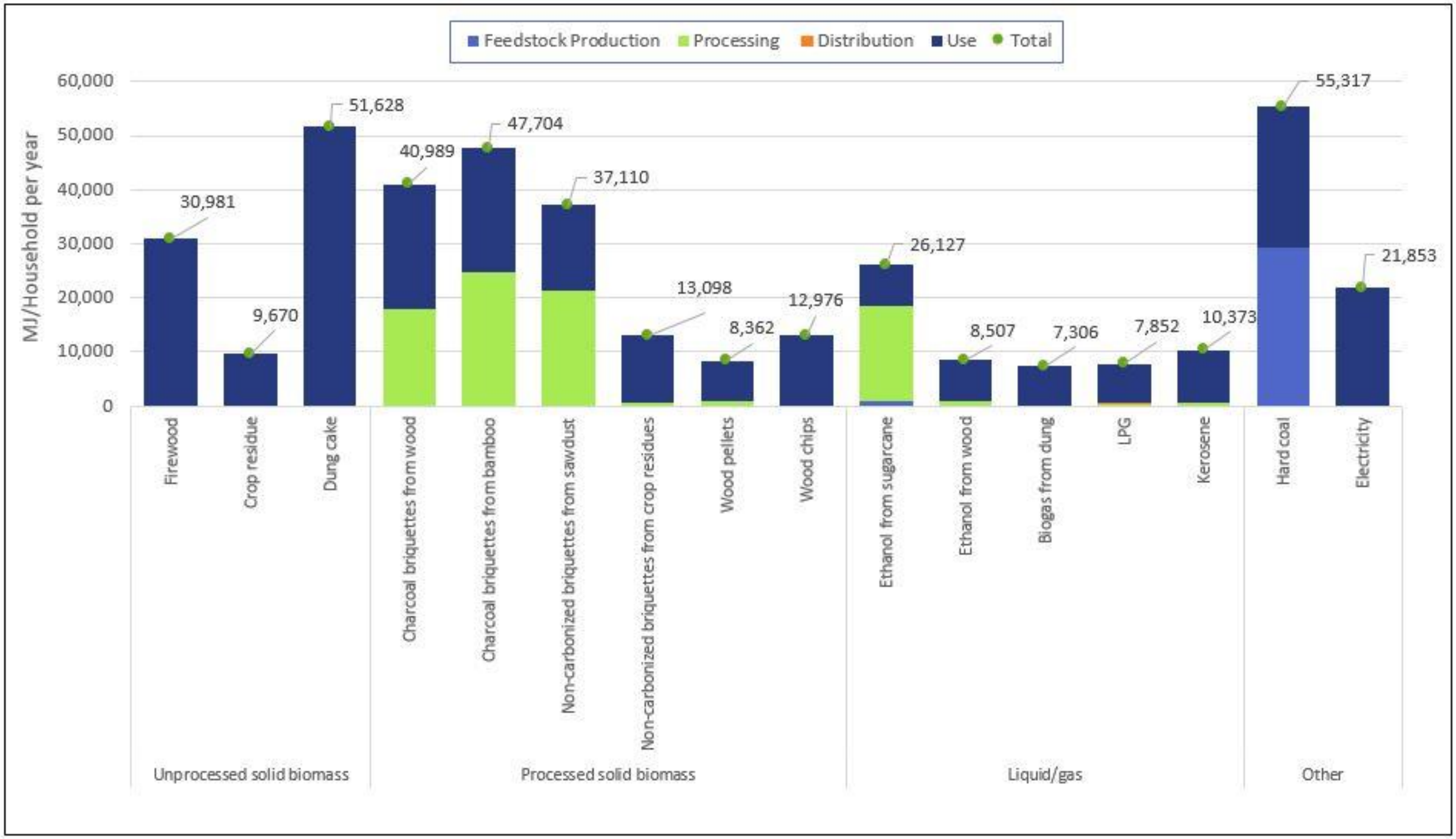


Figure A-13. Total Energy Demand (MJ) for Cooking Fuel Types (India)

To produce, distribute and use cooking fuels by a single household per year

A.3.2.2 Net Energy Demand

Table A-17 and Figure A-14 illustrate the net energy demand impact results for fuels in India by life cycle stage. Net energy demand is calculated in the same way as total energy demand, with the final energy delivered to the cooking pot deducted from the results. The net energy indicator is, therefore, the additional energy required for the life cycle of the cookstove fuel beyond what is delivered to the consumer for cooking purposes. For India, 11.0 MJ of cooking energy are consumed per household per day, which equates to 4,015 MJ per household per year.[72] Utilization of unprocessed solid biomass consumes 6.7 to 11.9 times more energy than is provided to the pot, as listed in the last column of Table A-17. Similar levels of net energy demand are seen for charcoal briquettes, non-carbonized briquettes from sawdust, hard coal and ethanol from sugarcane. The lowest overall net energy demand is calculated for non-carbonized briquettes from crop residues, wood pellets, wood chips, ethanol from wood, biogas from dung, LPG, and kerosene. Production, processing, distribution, and use of these less energy intensive fuels uses 0.82 to 2.3 times the amount of energy delivered to the pot.

Table A-17. Net Energy Demand (MJ) for Cooking Fuel Types (India)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total	Net Energy Consumed: Delivered Energy
		Feedstock Production	Processing	Distribution	Use		
Unprocessed solid biomass	Firewood	0	0	0	26,966	26,966	6.72
	Crop residue	0	0	0	5,655	5,655	1.41
	Dung cake	0	0	0	47,613	47,613	11.9
Processed solid biomass	Charcoal briquettes from wood	0	18,043	1.57	18,929	36,974	9.21
	Charcoal briquettes from bamboo	0	24,758	1.57	18,929	43,689	10.9
	Non-carbonized briquettes from sawdust	0	21,363	1.65	11,731	33,095	8.24
	Non-carbonized briquettes from crop residues	0	527	0.0050	8,556	9,083	2.26
	Wood pellets	0	775	12.3	3,560	4,347	1.08
	Wood chips	0	22.1	0.011	8,939	8,961	2.23
Liquid/gas	Ethanol from sugarcane	891	17,579	81.5	3,560	22,112	5.51
	Ethanol from wood	0	931	0.27	3,560	4,492	1.12
	Biogas from dung	0	0	0	3,291	3,291	0.82
	LPG	102	250	152	3,333	3,837	0.96
	Kerosene	135	374	116	5,734	6,358	1.58
Other	Hard coal	29,370	0	43.5	21,888	51,302	12.8
	Electricity	0	0	0	17,838	17,838	4.44

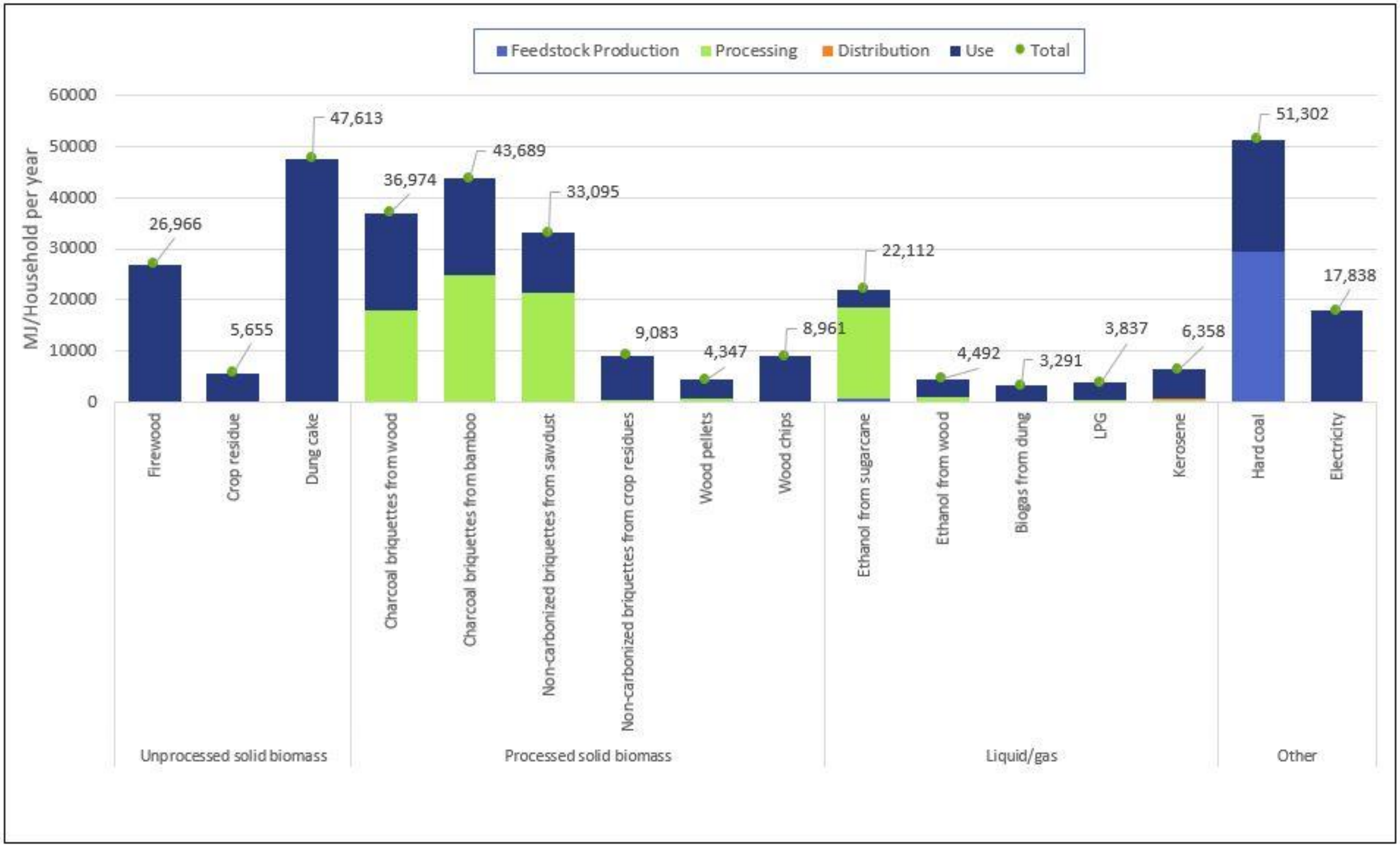


Figure A-14. Net Energy Demand (MJ) for Cooking Fuel Types (India)
To produce, distribute and use cooking fuels by a single household per year

A.3.2.3 Global Climate Change Potential (100a)

Table A-18 and Figure A-15 present the global climate change potential (GCCP) impact results for fuels in India by life cycle stage. The GCCP impact category represents the heat trapping capacity of greenhouse gases over a 100 year time horizon. Fossil fuel GCCP impacts are dominated by combustion emissions in the cookstove use stage. Coal has the highest impacts, since it is derived from non-renewable carbon and the thermal efficiency of coal stoves (15.5%) is relatively low compared to the other fossil fuel options (e.g., LPG stove efficiency is 57%). Electricity in India is derived from a mix of coal and petroleum fuels as well as some other sources such as hydropower, which is the primary reason its impacts fall between coal usage and fuels derived from crude oil or natural gas. For consistency, combustion emissions associated with electricity generation have been allocated to the use stage here, although emissions will not occur at the household level. Biogas GCCP impacts are primarily from methane leakage during the production of biogas in an anaerobic digester. Sugarcane ethanol, dung cake (from animals consuming biomass to produce the dung), crop residue (unprocessed and crop residues briquettes), and charcoal briquettes from bamboo are derived from renewable biomass that removed CO_2 from the atmosphere during growth; therefore, the CO_2 emissions released from combustion of these fuels is considered carbon neutral, as discussed in detail in the Appendix B methodology. Methane emissions from the animals producing the dung for the dung cake is also modeled as outside the system boundaries of this work, with these emissions being allocated to the primary animal product (e.g. dairy). Impacts for these renewable fuels during the use phase are driven by nitrous oxide and methane emissions during cookstove use. Impacts associated with fertilizer production and emissions from application also play a role in the sugarcane ethanol overall impacts.

Based on the trend in forest area and the annual generation of biomass per hectare, a little less than 60% of the firewood required for cooking can be sustainably sourced; therefore, the combustion emissions for the non-renewable 40% of wood are not considered carbon-neutral. This adjustment is also applied to other wood fuels (wood-derived charcoal briquettes, wood pellets and wood chips), but not to fuels derived from wood wastes (wood ethanol and non-carbonized briquettes from sawdust). With the cut-off modeling methodology used in this analysis, wood wastes are treated as a “free” product (all burdens are allocated to the primary wood product, e.g., lumber, which is outside the scope of this study), so emissions of biomass CO_2 for fuels derived from wood waste are treated as carbon neutral. For charcoal briquettes, GCCP impacts for carbonization of the wood in the kiln are comparable in magnitude to the emissions from combustion of the charcoal briquettes in a cookstove. Charcoal kiln impacts are largely driven by the methane emissions during the carbonization process. Combustion emissions for bamboo-derived charcoal briquettes are lower than for wood-derived charcoal briquettes because bamboo is a renewable crop and all combustion emissions are considered carbon-neutral, while only 60% of the wood combustion emissions (for the renewable percentage of the wood supply) are considered carbon-neutral.

Table A-18. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (India)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	2,166	2,166
	Crop Residue	0	0	0	530	530
	Dung Cake	0	0	0	765	765
Processed Solid Biomass	Charcoal Briquettes from Wood	0	1,100	116	1,082	2,298
	Charcoal Briquettes from Bamboo	0	831	116	184	1,132
	Non-Carbonized Briquettes from Sawdust	0	23.8	123	131	277
	Non-Carbonized Briquettes from Crop Residues	0	32.7	0.37	182	215
	Wood Pellets	0	112	4.42	567	683
	Wood Chips	0	1.77	0.80	641	644
Liquid/Gas	Ethanol from Sugarcane	320	21.2	39.0	3.84	384
	Ethanol from Wood	0	19.7	19.7	3.84	43.3
	Biogas from Dung	0	36.9	0	5.32	42.2
	LPG	19.4	37.9	48.3	1,100	1,206
	Kerosene	26.2	55.7	50.8	595	728
Other	Hard Coal	65.0	0	6.49	3,793	3,865
	Electricity	0	0	0	1,665	1,665

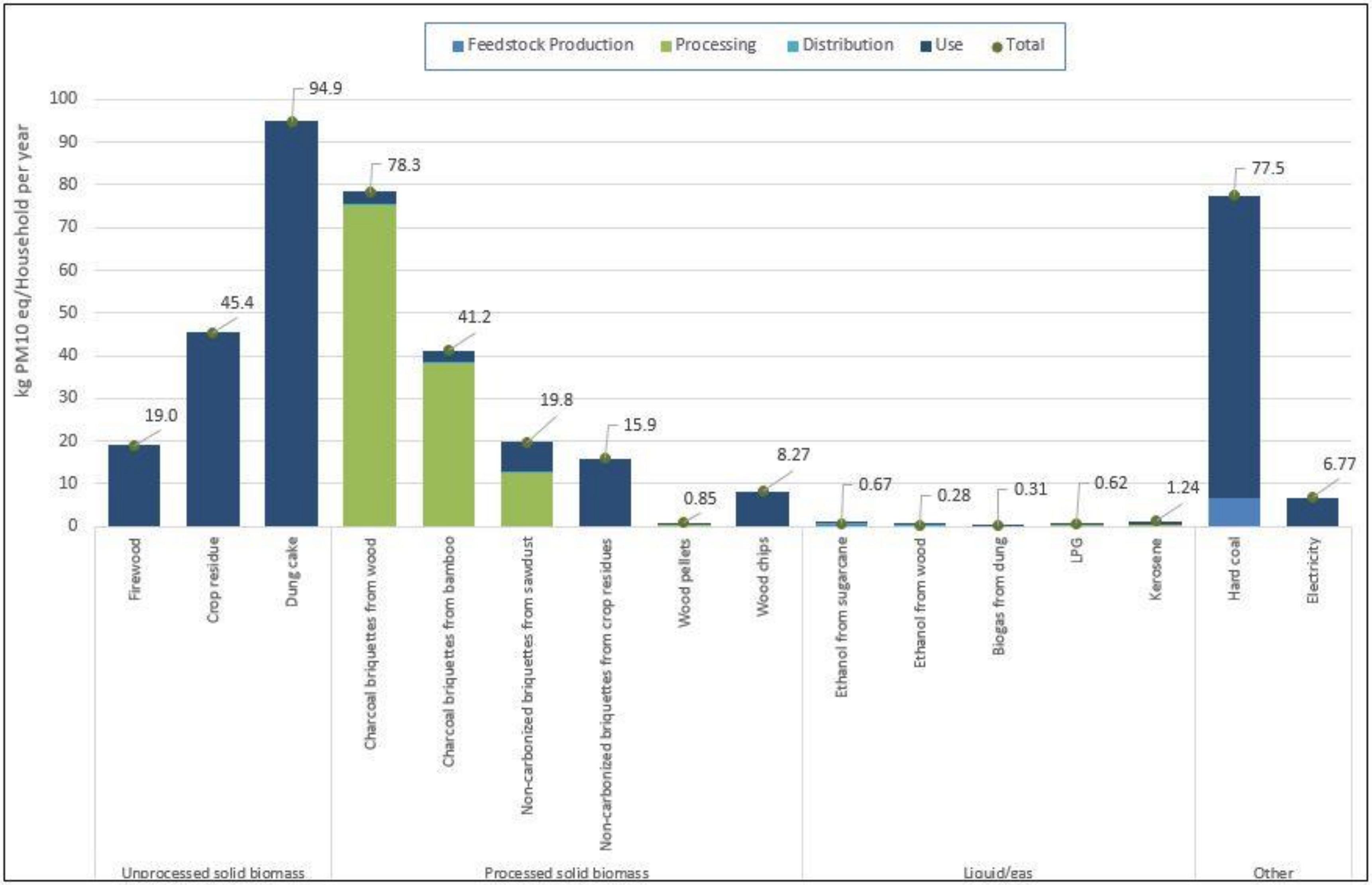


Figure A-15. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (India)

To produce, distribute and use cooking fuels by a single household per year

A.3.2.4 Black Carbon and Short-Lived Climate Pollutants

Table A-19 and Figure A-16 display the black carbon and short-lived climate pollutants impact results for fuels in India by life cycle stage. Black carbon (BC) is formed by incomplete combustion of fossil and bio-based fuels. BC is the carbon component of particulate matter (PM) with aerodynamic diameter less than or equal to 2.5 microns (PM2.5). This is the size of PM that most strongly absorbs light and thus has potential radiative forcing effects (i.e., potential to contribute to global warming). Potential climate forcing impacts resulting from BC emissions include direct, albedo (i.e., fraction of solar energy hitting the earth that is reflected), and other effects. BC is emitted with other particles (e.g. organic carbon) and criteria pollutants such as nitrogen and sulfur dioxides. Though some of these co-pollutants may exert a cooling effect on climate, the net effects of BC emissions likely contribute to global climate warming. Appendix B shows the 20 year global warming potential and black carbon equivalent values used in the results calculation. Results are presented here based on BC equivalents. The highest BC impacts are seen for traditional unprocessed biomass fuels as well as charcoal briquettes and hard coal, which tend to have high particulate matter emissions when combusted. Similarly, high emissions of particulate matter are seen in the charcoal kiln, which combusts wood to carbonize the fuel. Utilization of the liquid and gas fuels result in the lowest overall BC impacts. Some life cycle stages have negative BC equivalent impacts, which is the case when emissions of SO_x and organic carbon, pollutants with net cooling effects on the climate, are greater than the emissions of BC and other co-emitted pollutants that lead to short term warming impacts.

Table A-19. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (India)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	4.19	4.19
	Crop Residue	0	0	0	9.72	9.72
	Dung Cake	0	0	0	20.1	20.1
Processed Solid Biomass	Charcoal Briquettes from Wood	0	16.1	0.0078	1.03	17.2
	Charcoal Briquettes from Bamboo	0	8.54	0.0078	1.03	9.58
	Non-Carbonized Briquettes from Sawdust	0	0.23	0.0082	1.54	1.78
	Non-Carbonized Briquettes from Crop Residues	0	-0.0015	2.5E-05	3.37	3.37
	Wood Pellets	0	-0.0040	3.6E-04	0.084	0.080
	Wood Chips	0	4.2E-04	5.4E-05	1.78	1.79
Liquid/Gas	Ethanol from Sugarcane	-0.0069	-0.029	0.0032	0.011	-0.022
	Ethanol from Wood	0	0.0066	0.0013	0.011	0.019
	Biogas from Dung	0	0	0	0.027	0.027
	LPG	0.0023	0.018	0.0033	0.022	0.045
	Kerosene	7.6E-04	0.0089	0.0010	0.034	0.045
Other	Hard Coal	1.36	0	5.2E-05	14.4	15.7
	Electricity	0	0	0	-0.076	-0.076

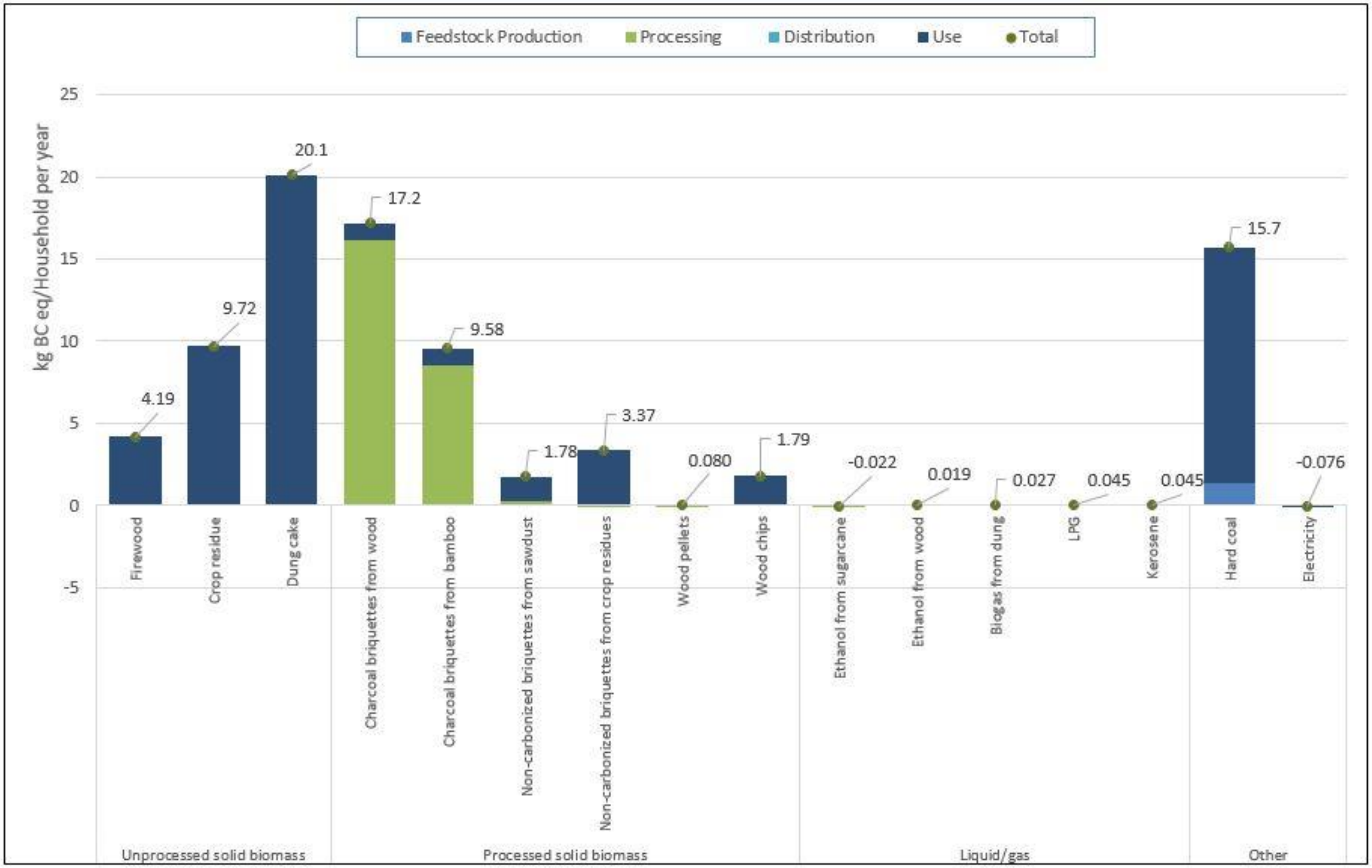


Figure A-16. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (India)
To produce, distribute and use cooking fuels by a single household per year

A.3.2.5 Particulate Matter Formation Potential

Table A-20 and Figure A-17 show the particulate matter formation impact results for fuels in India by life cycle stage. Particulate matter can contribute to many negative health impacts such as effects on breathing and respiratory systems, damage to lung tissue, cancer, and premature death. Primary and secondary pollutants leading to particulate matter formation as well as PM2.5 are characterized here to kg PM10 eq. Traditional biomass fuels and hard coal lead to the greatest particulate matter formation impacts, with dung cake having the highest overall impacts. Most particulate matter formation impacts occur during cookstove use at the household with the exception of charcoal briquettes, where the carbonization of the wood in the kiln dominates the overall life cycle impacts. Charcoal briquettes from bamboo have slightly lower particulate matter impacts than wood charcoal briquettes. This is because a larger portion of bamboo charcoal briquettes are estimated to be produced in brick kilns; whereas, all wood charcoal briquettes in India are assumed to be produced in traditional earth mound kilns. Processing of commercial non-carbonized sawdust briquettes results in particulate matter formation pollutants from combusting a portion of the briquette output to dry the briquettes. Advanced liquid fuels as well as biogas and wood pellets have comparably small particulate matter impacts. Most of the particulate matter impacts for electricity are derived from the coal mix in the average Indian electrical grid. The particulate matter impacts from fuel combustion for electricity generation have been allocated to the use phase, although the actual particulate matter emissions for electricity do not occur at the household level.

Table A-20. Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (India)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	19.0	19.0
	Crop Residue	0	0	0	45.4	45.4
	Dung Cake	0	0	0	94.9	94.9
Processed Solid Biomass	Charcoal Briquettes from Wood	0	75.3	0.20	2.80	78.3
	Charcoal Briquettes from Bamboo	0	38.2	0.20	2.80	41.2
	Non-Carbonized Briquettes from Sawdust	0	12.7	0.21	6.92	19.8
	Non-Carbonized Briquettes from Crop Residues	0	0.13	6.4E-04	15.7	15.9
	Wood Pellets	0	0.43	0.011	0.41	0.85
	Wood Chips	0	0.0067	0.0014	8.26	8.27
Liquid/Gas	Ethanol from Sugarcane	0.46	0.14	0.071	0.0017	0.67
	Ethanol from Wood	0	0.24	0.034	0.0017	0.28
	Biogas from Dung	0	0	0	0.31	0.31
	LPG	0.036	0.25	0.10	0.24	0.62
	Kerosene	0.049	0.35	0.094	0.75	1.24
Other	Hard Coal	6.65	0	0.015	70.8	77.5
	Electricity	0	0	0	6.77	6.77

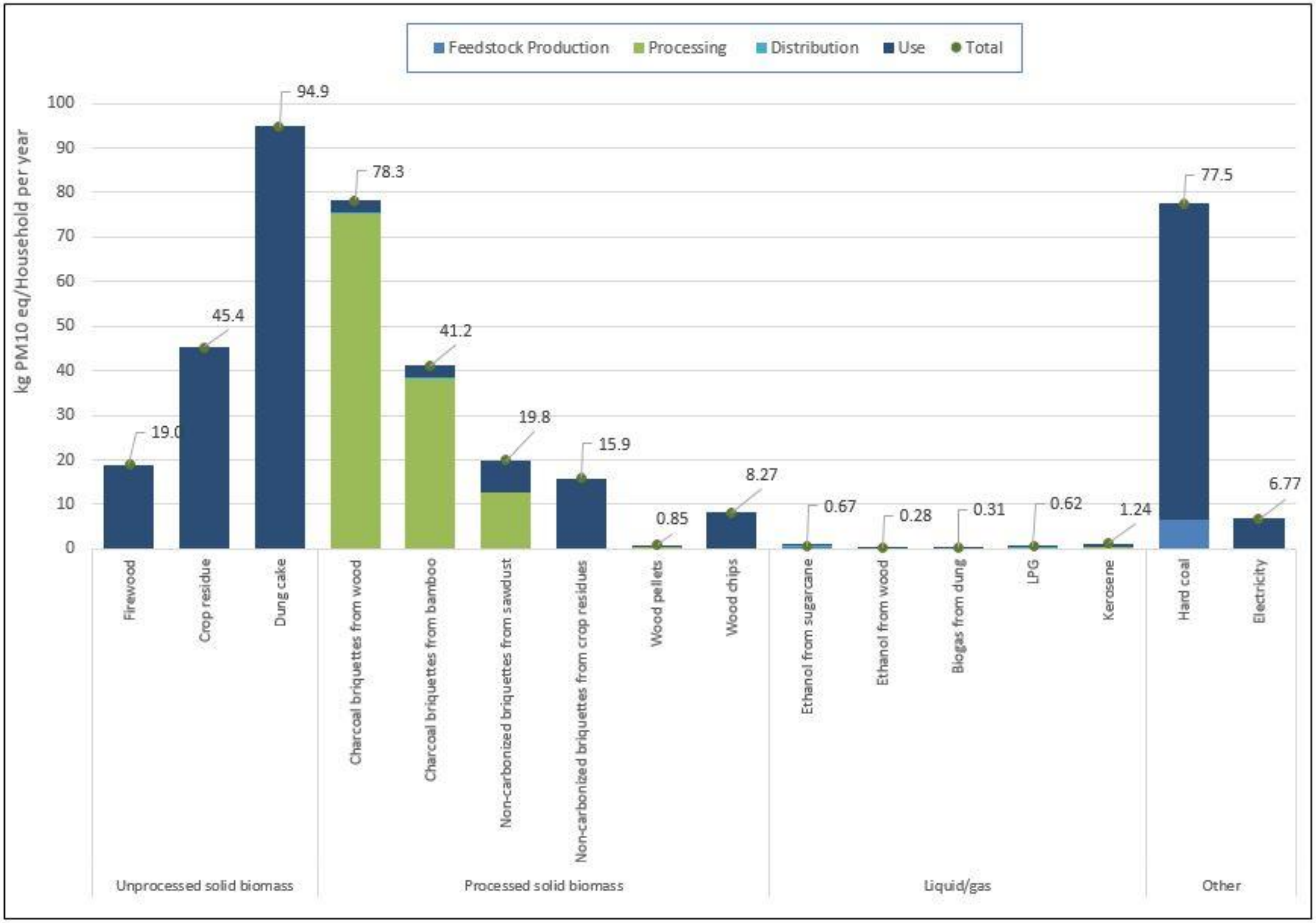


Figure A-17. Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (India)
To produce, distribute and use cooking fuels by a single household per year

A.3.2.6 Fossil Fuel Depletion

Table A-21 and Figure A-18 provide the fossil fuel depletion impact results for fuels in India by life cycle stage. Fossil depletion captures the consumption of fossil fuels, primarily coal, natural gas, and crude oil. All fuels are normalized to kg oil eq based on the heating value of the fossil fuel relative to the heating value of a kg of oil. The fossil depletion associated with traditional biomass fuels as well as biogas and ethanol from wood is negligible, as these fuels are not derived from fossil fuel, and collection of these fuels is done manually. While biomass fuels are not derived from fossil fuels, some fossil fuels may be consumed across the life cycle of these fuels for energy inputs to fuel production and processing, distribution, and disposal. Fossil depletion for biomass pellets is associated with electricity usage for pelletization and some transport, while sugarcane ethanol fossil depletion is primarily from fertilizers during cane production, as well as diesel for farm operation and distribution of the feedstock and fuel. Some fossil depletion impacts are also seen for processing the wood chips and non-carbonized briquettes for the portions of these fuels that are not processed manually (as discussed in detail in Appendix B, 50% of non-carbonized and carbonized wood/bamboo briquetting is modeled as mechanized in India, and 13% of wood chipping is modeled as mechanized in India). Fossil depletion impacts are highest for coal, LPG, kerosene and electricity as these sources of energy rely on fossil fuels. The greatest impacts are seen for coal. Although coal has a lower heating value per kg compared to crude oil or natural gas, the lower coal stove thermal efficiency (15.5%) compared to the more efficient LPG stoves (57%) means that more coal must be burned to get the same amount of cooking energy, leading to the higher fossil depletion for cooking with coal compared to LPG.

Table A-21. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (India)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total
		Feedstock Production	Processing	Distribution	Use	
Unprocessed solid biomass	Firewood	0	0	0	0.026	0.026
	Crop residue	0	0	0	0.030	0.030
	Dung cake	0	0	0	0.62	0.62
Processed solid biomass	Charcoal briquettes from wood	0	0.41	0.038	0.025	0.47
	Charcoal briquettes from bamboo	0	0.40	0.038	0.062	0.50
	Non-carbonized briquettes from sawdust	0	5.24	0.040	0.011	5.29
	Non-carbonized briquettes from crop residues	0	7.20	1.2E-04	0.011	7.21
	Wood pellets	0	23.6	1.49	7.2E-04	25.1
	Wood chips	0	0.53	2.7E-04	0.011	0.54
Liquid/gas	Ethanol from sugarcane	48.9	11.2	13.2	0	73.4
	Ethanol from wood	0	4.29	0.0064	0	4.30
	Biogas from dung	0	0	0	0	0
	LPG	2.61	6.38	3.89	188	201
	Kerosene	3.43	9.51	2.94	248	264
Other	Hard coal	517	0	0.77	456	974
	Electricity	0	0	0	367	367

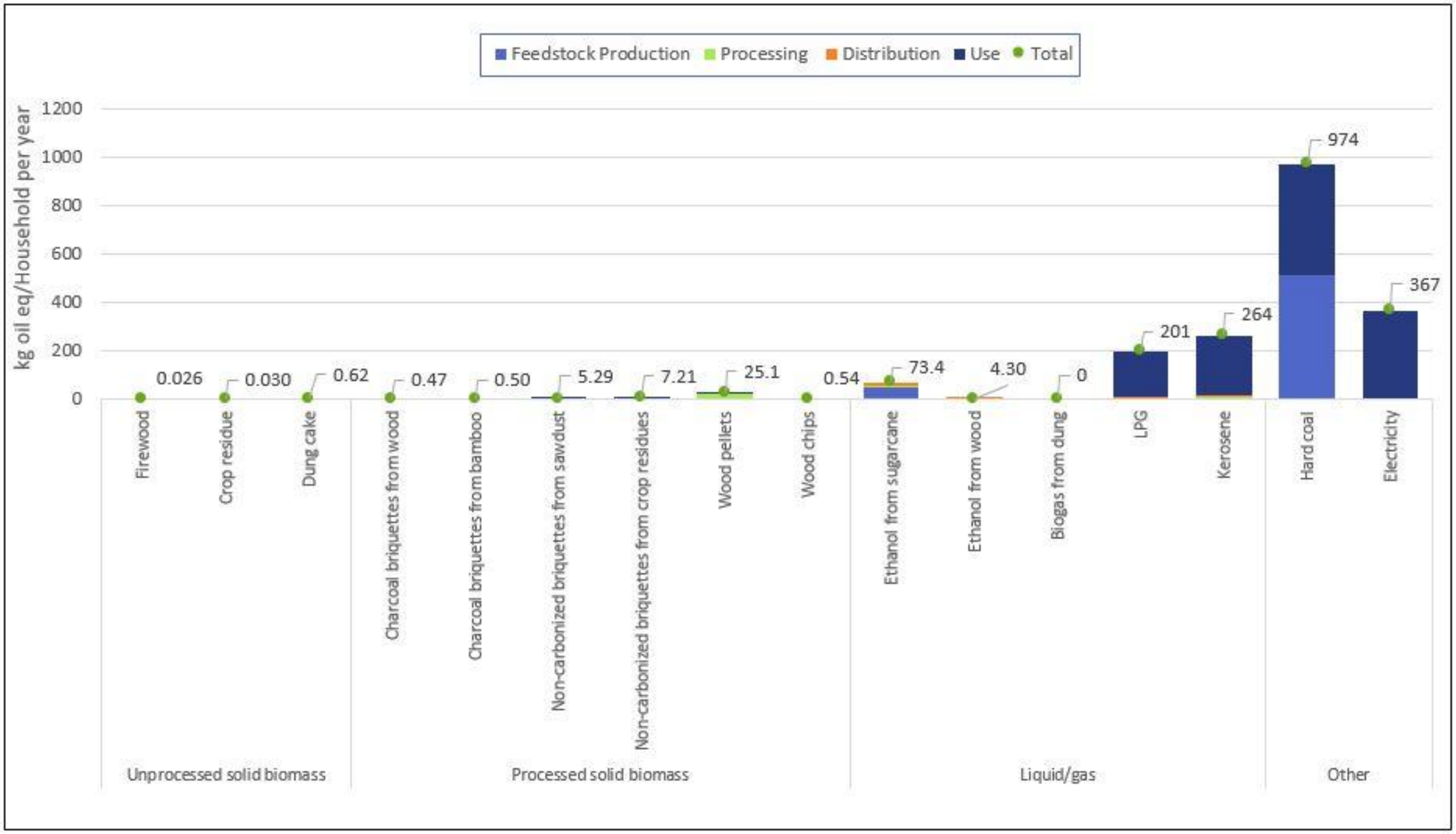


Figure A-18. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (India)
To produce, distribute and use cooking fuels by a single household per year

A.3.2.7 Water Depletion

Table A-22 and Figure A-19 illustrate the water depletion impact results for fuels in India by life cycle stage. Water depletion results are based on the volume of fresh water inputs over the life cycle of the assessed fuels. Water may be incorporated in the fuel product, evaporated, or returned to the same or different water body or to land. If the water is returned to the same water body, it is assumed the water is returned at a degraded quality, and therefore is considered consumptive use. Water consumption includes evaporative losses from establishment of hydroelectric dams but does not include the water passing through the turbine, since that water is not removed from its source. The hydropower in the electricity mix drives the overall water depletion impacts. In this case, for simplicity, electricity impacts have been allocated to the use life cycle stage. Water depletion associated with wood pellets and biomass briquettes is also due to electricity usage during pelletization/briquetting. Water depletion impacts are also notable for sugarcane ethanol, as irrigation is required for the cane production. Some water depletion impacts are also seen for the biogas to maintain the digester, but these are negligible when compared to the evaporative losses from hydropower in the electricity grid. Water depletion impacts are negligible for the traditional biomass fuels, which are not irrigated. Because the water content of these fuels comes from the atmosphere as rainfall, the water released back to the atmosphere when the biomass is dried or combusted is not considered consumptive use.

Table A-22. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (India)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	0.20	0.20
	Crop Residue	0	0	0	0.23	0.23
	Dung Cake	0	0	0	4.76	4.76
Processed Solid Biomass	Charcoal Briquettes from Wood	0	2.34	3.6E-04	0.19	2.53
	Charcoal Briquettes from Bamboo	0	2.26	3.6E-04	0.19	2.45
	Non-Carbonized Briquettes from Sawdust	0	29.5	3.8E-04	0.081	29.6
	Non-Carbonized Briquettes from Crop Residues	0	40.5	1.1E-06	0.081	40.6
	Wood Pellets	0	132	10.8	0.0035	143
	Wood Chips	0	0.55	2.5E-06	0.085	0.63
Liquid/Gas	Ethanol from Sugarcane	222	53.7	79.6	0	356
	Ethanol from Wood	0	1.12	6.1E-05	0	1.12
	Biogas from Dung	0	4.18	0	0	4.18
	LPG	4.55	19.3	99.4	0	123
	Kerosene	6.14	28.5	111	0	146
Other	Hard Coal	1.51	0	34.3	30.9	66.7
	Electricity	0	0	0	2,066	2,066

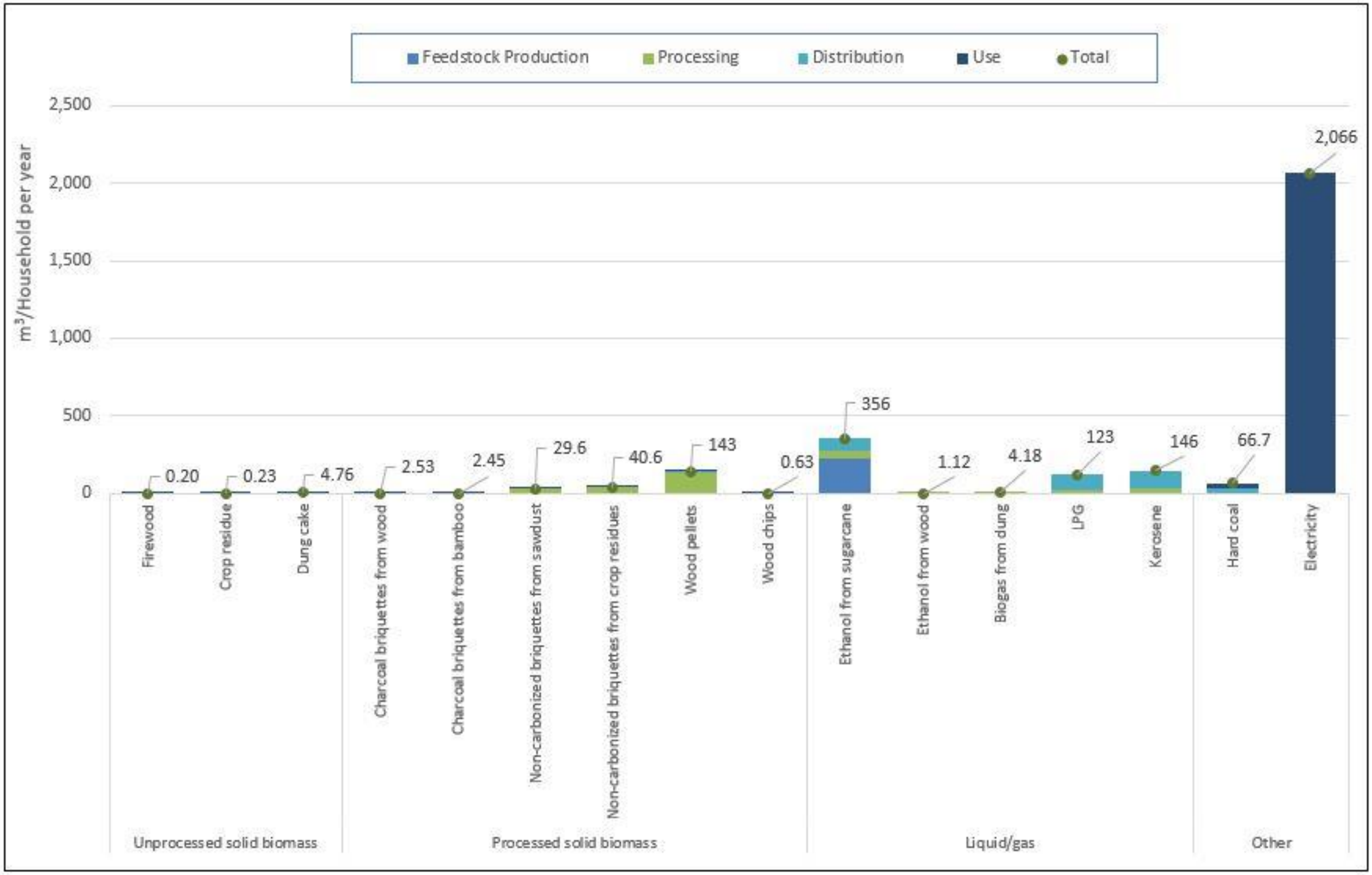


Figure A-19. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (India)
To produce, distribute and use cooking fuels by a single household per year

A.3.2.8 Terrestrial Acidification Potential

Table A-23 and Figure A-20 show the terrestrial acidification potential impact results for fuels in India by life cycle stage. Terrestrial acidification quantifies the acidifying effect of substances on their environment. Important contributing emissions include SO_2, NO_x, and NH_3. Acidification impacts are dominated by coal usage, either as a direct fuel or as an input to electricity generation. Electricity usage for pelletization drive biomass pellet acidification impacts. Sulfur dioxide emissions from coal are notably higher than sulfur dioxide emissions from combustion of other fuels. Ethanol contains no sulfur, so there are no sulfur dioxide emissions, a main cause of acidification, for the ethanol cookstove use stage. No NO_x emissions data for ethanol combustion in a cookstove were available, although qualitative reports stated that ethanol combustion leads to minimal nitrogen oxide emissions. Traditional fuels, specifically crop residues and dung cake, have slightly higher acidification impacts than the liquid fuels. The main contributing emissions leading to acidification potential for the traditional fuels are SO_x and NO_x. For instance, NO_x leads to 70% and SO_x leads to 30% of the crop residue acidification impacts, respectively. Distribution acidification impacts in India are highest for transportation of the carbonized and non-carbonized briquettes since a greater mass of input fuel for the solid biomass is required to be transported a longer distance given the proximity of end users to forests in India (Appendix B provides detailed discussions of the model's transportation parameters). The lowest overall acidification impacts are seen for biogas. Because land applied digested sludge from biogas production is used by another product system, it is considered to be outside the system boundaries for this analysis; however, it is possible that this land applied digested sludge could lead to emissions of ammonia, an acidifying substance.

Table A-23. Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (India)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total
		Feedstock Production	Processing	Distribution	Use	
Unprocessed Solid Biomass	Firewood	0	0	0	1.60	1.60
	Crop Residue	0	0	0	2.47	2.47
	Dung Cake	0	0	0	3.01	3.01
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.035	0.48	0.82	1.34
	Charcoal Briquettes from Bamboo	0	0.033	0.48	0.82	1.34
	Non-Carbonized Briquettes from Sawdust	0	0.33	0.51	0.66	1.49
	Non-Carbonized Briquettes from Crop Residues	0	0.31	0.0015	0.86	1.17
	Wood Pellets	0	1.01	0.025	0.13	1.17
	Wood Chips	0	0.013	0.0033	0.70	0.72
Liquid/Gas	Ethanol from Sugarcane	1.23	0.61	0.16	0	2.00
	Ethanol from Wood	0	0.29	0.082	0	0.37
	Biogas from Dung	0	0	0	0.43	0.43
	LPG	0.068	0.54	0.23	0.46	1.29
	Kerosene	0.092	0.68	0.21	0.62	1.60
Other	Hard Coal	0.31	0	0.038	7.17	7.51
	Electricity	0	0	0	16.1	16.1

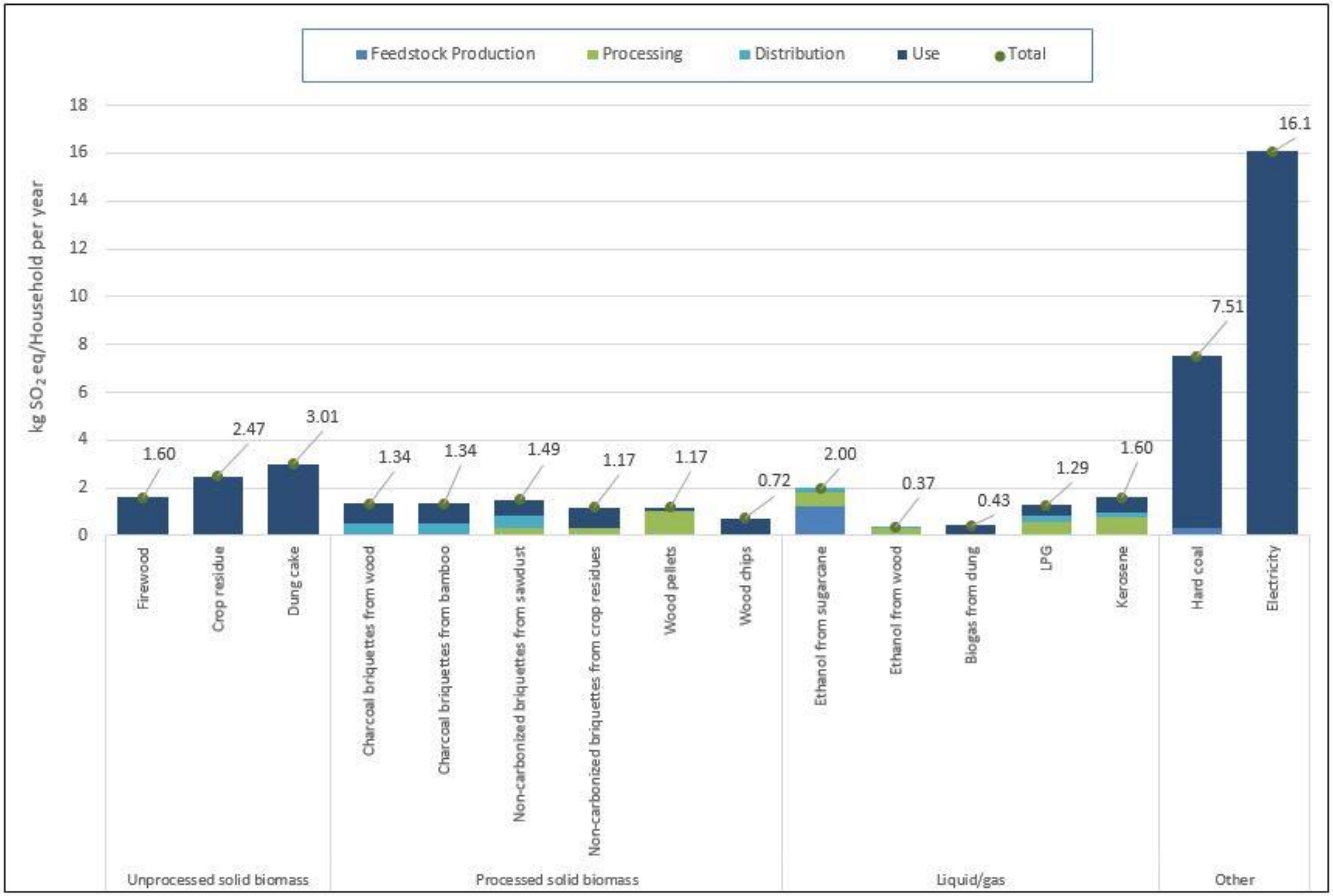


Figure A-20. Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (India)
To produce, distribute and use cooking fuels by a single household per year

A.3.2.9 Freshwater Eutrophication Potential

Table A-24 and Figure A-21 provide the freshwater eutrophication potential impact results for fuels in India by life cycle stage. Eutrophication assesses the impacts from excessive load of macro-nutrients to the environment and eventual deposition in freshwater, which can result in algal blooms, oxygen depletion, and fish kills. Pollutants contributing to this category are all P based (e.g. phosphate, phosphoric acid, phosphorus). Dung cake results in the highest eutrophication potential impacts. This is due to the much larger ash quantity produced from dung cake compared to all other fuels. The ash from the traditional fuels, which contains phosphorus is assumed to be land applied, which leads to soil emissions and eventual runoff into freshwater. Ash production is also the reason other traditional fuels have a relatively high eutrophication impact. While impacts are comparably smaller for ethanol, there are some eutrophication impacts occurring from use of phosphorus based fertilizer in sugarcane production. There are no eutrophication impacts associated with biogas. Application of the digested sludge from the biogas system would likely lead to some eutrophication impacts, but utilization of this useful co-product is outside the system boundaries of this study. The digested sludge impacts are allocated to the product system it serves (i.e. nutrients for crop production). Impacts from fossil based fuels and biomass pellets are minimal compared to the traditional fuels. The non-carbonized processed biomass fuels have slightly lower eutrophication potential impacts than traditional unprocessed biomass fuels. Because processed biomass burns more efficiently than unprocessed biomass, less fuel must be burned, leading to an overall lower quantity of ash produced.

Table A-24. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (India)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	0.63	0.63
	Crop Residue	0	0	0	0.75	0.75
	Dung Cake	0	0	0	15.3	15.3
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.51	4.2E-07	0.61	1.12
	Charcoal Briquettes from Bamboo	0	0.25	4.2E-07	0.61	0.86
	Non-Carbonized Briquettes from Sawdust	0	0.039	4.4E-07	0.26	0.30
	Non-Carbonized Briquettes from Crop Residues	0	2.7E-04	1.3E-09	0.26	0.26
	Wood Pellets	0	0.0011	0.0013	0.011	0.014
	Wood Chips	0	7.9E-05	2.9E-09	0.27	0.27
Liquid/Gas	Ethanol from Sugarcane	0.13	0.0085	0.0063	4.3E-06	0.15
	Ethanol from Wood	0	8.8E-06	7.0E-08	4.3E-06	1.3E-05
	Biogas from Dung	0	0	0	0	0
	LPG	5.3E-05	0.0025	0.0021	0.0062	0.011
	Kerosene	7.2E-05	0.0039	0.0092	0	0.013
Other	Hard Coal	3.0E-05	0	0.0046	0.0040	0.0086
	Electricity	0	0	0	0.014	0.014

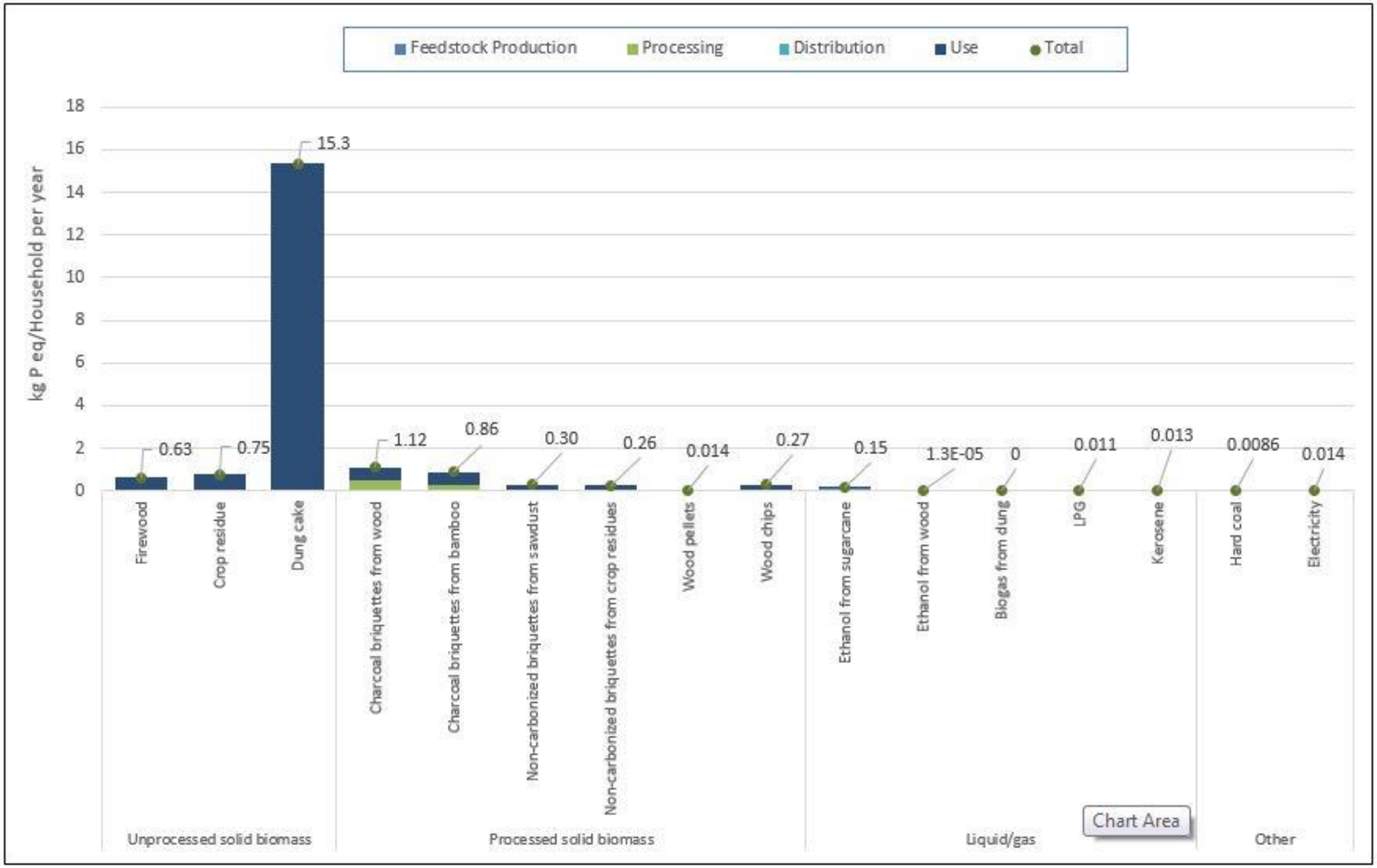


Figure A-21. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (India)
To produce, distribute and use cooking fuels by a single household per year

A.3.2.10 Photochemical Oxidant Formation Potential

Table A-25 and Figure A-22 present the photochemical oxidant formation potential impact results for fuels in India by life cycle stage. The photochemical oxidant formation (i.e. smog formation) results are an indicator of the potential for formation of reactive substances that cause harm to human health and vegetation. Results are characterized here to kg of non-methane volatile organic compounds (NMVOC) eq. Some key emissions for cookstove fuel systems that contribute to photochemical oxidant formation include carbon monoxide, methane, nitrogen oxides, NMVOCs, and sulfur dioxide. Traditional biomass fuels and hard coal lead to the greatest photochemical formation impacts, with dung cake having the highest overall impacts. For charcoal briquettes, impacts are split between the fuel processing stage (carbonization in a kiln) and the use stage. Higher emissions of NMVOCs were documented for the brick kilns used to produce bamboo charcoal briquettes compared to the earth mound kilns used for wood charcoal briquettes, leading to the overall higher photochemical oxidant formation seen for bamboo charcoal briquettes relative to charcoal briquettes from wood. Photochemical oxidant impacts for electricity are primarily associated with utilization of hard coal in the grid mix. Impacts from fuel combustion emissions for electricity generation have been allocated to the use stage here for simplicity, but impacts do not occur at the household level. Photochemical oxidant formation impacts are relatively small for the liquid fuels, processed non-carbonized biomass and biogas.

Table A-25. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (India)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	24.2	24.2
	Crop Residue	0	0	0	35.1	35.1
	Dung Cake	0	0	0	74.9	74.9
Processed Solid Biomass	Charcoal Briquettes from Wood	0	21.3	0.83	20.2	42.3
	Charcoal Briquettes from Bamboo	0	53.0	0.83	20.2	74.0
	Non-Carbonized Briquettes from Sawdust	0	1.59	0.87	9.96	12.4
	Non-Carbonized Briquettes from Crop Residues	0	0.15	0.0026	12.2	12.3
	Wood Pellets	0	0.50	0.039	0.41	0.95
	Wood Chips	0	0.023	0.0057	10.5	10.5
Liquid/Gas	Ethanol from Sugarcane	0.68	0.19	0.26	0.25	1.37
	Ethanol from Wood	0	0.51	0.14	0.25	0.90
	Biogas from Dung	0	0.015	0	0.44	0.46
	LPG	0.086	0.49	0.32	2.02	2.92
	Kerosene	0.12	0.74	0.33	3.46	4.65
Other	Hard Coal	0.58	0	0.042	31.0	31.6
	Electricity	0	0	0	8.08	8.08

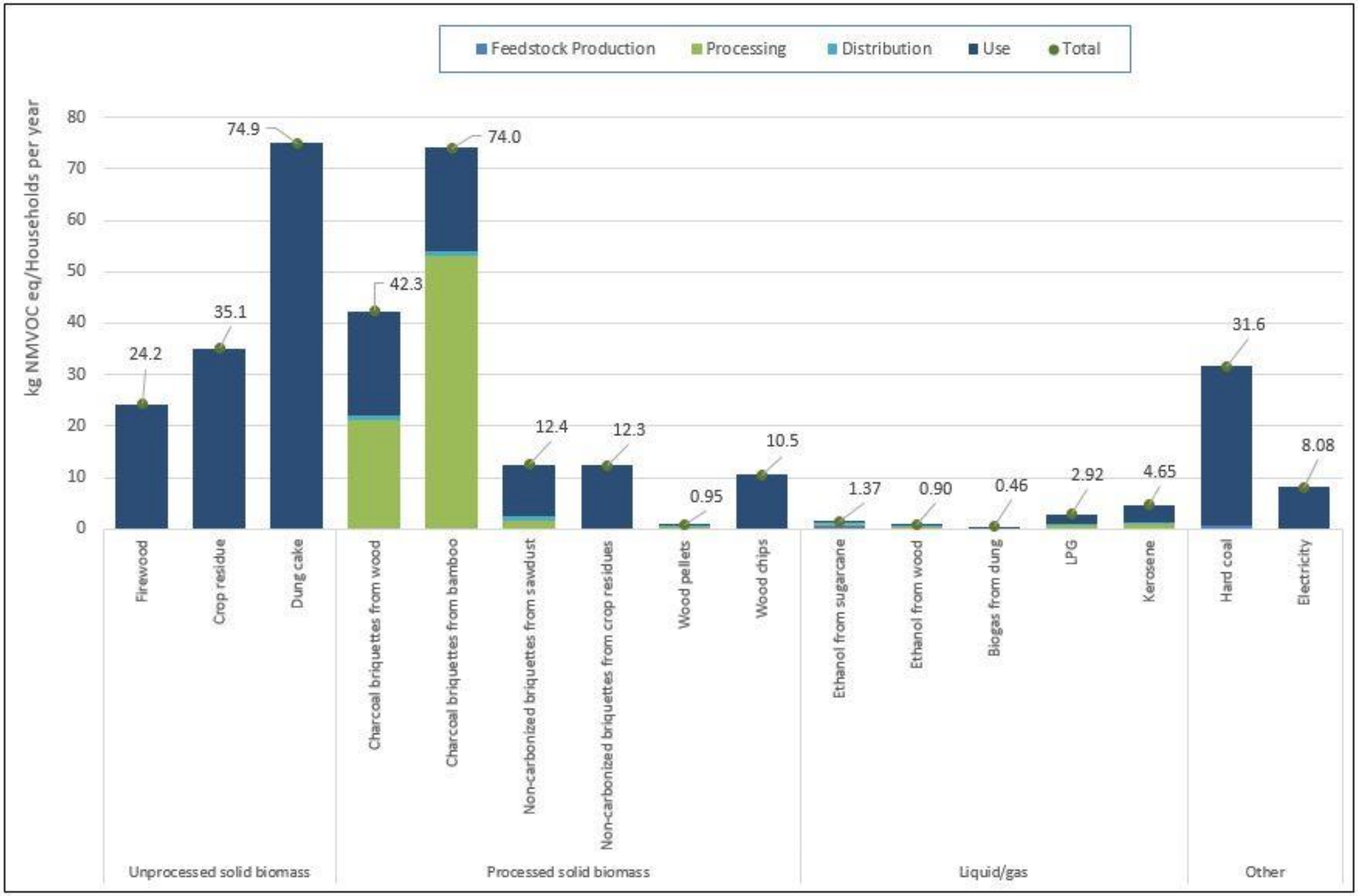


Figure A-22. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (India)
To produce, distribute and use cooking fuels by a single household per year

A.3.3 Economic Indicators for India

Discussions of the economic indicators are separated by rural and urban regions where possible. Some discussion of economic indicators may include cooking fuels that were not within the overall scope of this analysis, but are available and pertinent to the economic discussion due to parallel work performed for EPA.

A.3.3.1 Fuel Use

Overall, the current cooking fuels used within India are heavily reliant on available biomass feedstocks, including firewood and crop residues. India has a mix of deforestation in the east as well as afforestation in the northern and southern part of the country. Figure A-23 provides the overall percentages of fuels currently used for household cooking in India. These fuels are broken out by urban and rural use in Figure A-24.

Wood fuel, such as firewood and brush, makes up 49 percent of the cooking fuel used by all households in India. In rural areas, almost two-thirds of the households still use firewood, and approximately 70 percent of the rural households using firewood collect it. Women and children commonly collect enough firewood or brush for 2-3 days use at one time. The poorer population, who would normally collect the firewood for cooking, do not consider their time to have economic value. Due to this concept, gathering firewood is ascertained to be a free fuel.[73] The population in certain areas of rural India may need to purchase firewood during the monsoon season. In urban areas, approximately 20 percent of homes use wood fuels for cooking, and more than 75 percent of the urban households using firewood purchase it from vendors.[74] The poorer urban population generally purchases fuels such as firewood and charcoal.

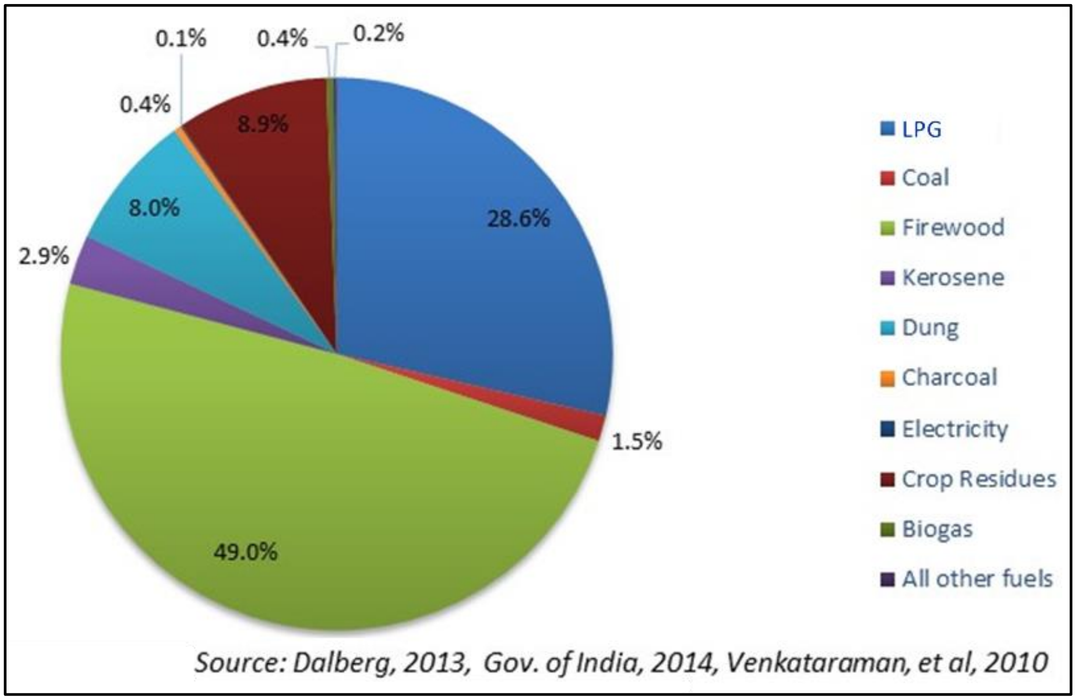


Figure A-23. Current Cooking Fuel Mix in India

During the turn of the century, the Indian government aggressively promoted LPG for use as a cleaner fuel. Government subsidies are available to help the population shift to LPG as a cleaner fuel. These subsidies reduce the net price of LPG to consumers by more than half. Recently the Indian government revised the subsidy program for LPG. This is discussed further in the social issues section, Government Policies/Programs. These subsidies have assisted the households within the urban cores to increase their use of LPG to almost two-thirds of the cooking fuel used. Much of this increase is in the middle and higher income classes. Only 10 percent of rural households are using LPG due to a number of factors, including cost and distribution issues. Poorer rural households are not able to afford larger canisters of LPG; however, smaller cylinders are being considered by the petroleum industry in India. The rural population may have to travel up to 10 km to retrieve cylinders of LPG, which takes time, and the distributor of the cylinders may not have it available due to erratic LPG supply in these areas.[75]

Kerosene is used in approximately 3 percent of the total households in India. Most of this use is in urban settings. Kerosene is subsidized by the government. A quota of kerosene is provided at a cheaper price depending on income level.[76] This fuel is in flux due to some wanting to ban its use.

In the rural areas, over 20 percent of the population are using crop residues or dung as cooking fuel. These fuels are considered free and have been used for decades, even centuries, in some areas of India. These fuels are used by only 1 percent of the urban population as they are not readily available for collection in urban areas.

Approximately 3 percent of the population use kerosene as a cooking fuel, this is mostly in the urban areas. Large universal price subsidies for kerosene are provided by the Indian government. Although it is a much cleaner fuel than biomass burning, issues with spills and burns when using kerosene are prohibitive to its use.

Only two-thirds of the households in the rural areas have access to electricity, while most households within urban areas have electricity available.[77] Although electricity is available to a large percentage of the population, it is not commonly used for cooking within India. It is an expensive fuel, and has issues of unreliability due to power cuts in rural areas in many states for up to 10-15 hours a day.[78]

Biogas (used by 0.3 percent of the households) is mainly used in the rural areas of India as it is produced from the dung of animals owned by the households. Many of the other fuels considered in this analysis, such as charcoal from bamboo, briquettes from crop residues, and ethanol, are produced by small enterprises at this time.

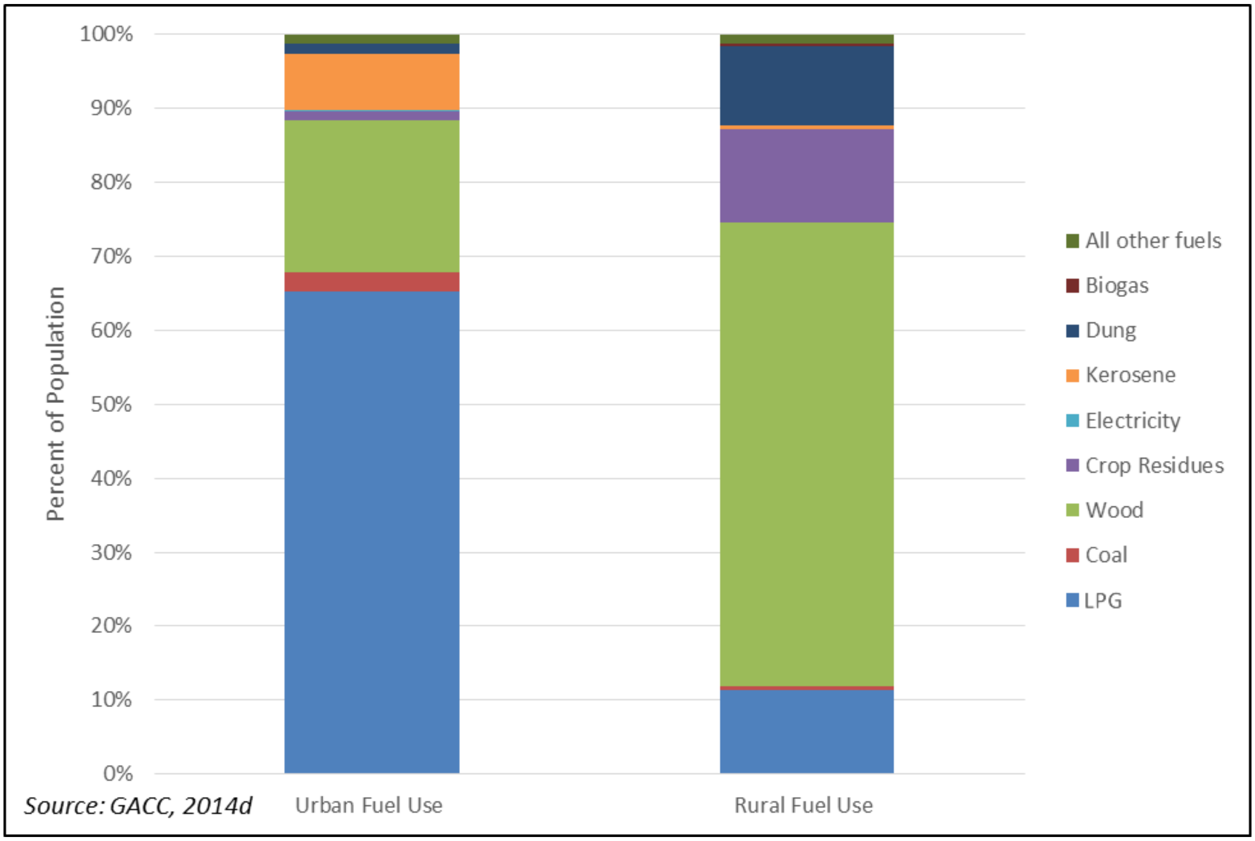


Figure A-24. 2013 Cooking Fuel Mix Comparing Urban and Rural Fuel Use in India

A.3.3.2 Fuel Imports, Exports, Production, and Demand in India

Table A-26 shows the levels of imports, exports, production, and demand (assumed to be equal to current consumption) of several fuels in India. Significant quantities of several cookstove fuels used in India are imported. According to the United Nations Statistics Division, in 2011 just over 8.5 million tonnes of LPG was imported into India, representing more than 50 percent of total demand. Wood fuels in the form of logs, pellets, and chips are also imported, but it is unknown whether these are used as cooking fuels versus other uses. Over 26 thousand tonnes of ethanol were imported in 2013; however, ethanol is likely being utilized for vehicle fuel or alcohol.

There is a surplus of LPG in India as imports and domestic production (less exports) combine to meet approximately 110 percent of total demand. A large amount of ethanol is also produced within India with little used for cooking purposes. The Food and Agriculture Organization and the UN Statistics Division state that almost 308 million tonnes of wood and 2.9 million tonnes of charcoal were produced in India in 2013. India also produces significant quantities of bamboo—approximately 100,000 kg of net exports—however, bamboo grown within India is mostly used for construction, furniture or uses other than fuels.[79]

Table A-26. Fuel Imports, Exports, Production, and Demand in India (Tonnes per Year)

Fuel	Imports	Exports	Production	Demand		Sources
				Total	Household	
LPG	8,534,000	174,000	9,547,000	16,237,000	13,319,000	UNSD, 2011
Ethanol	26,268	15,309	2,102,363	188,839	No data	UNSD, 2013 OECD/FAO, 2014
Firewood	4,168	94	307,709,300	No data	No data	UNSD, 2013 FAO, 2014
Charcoal Briquettes	2,000	31,000	2,880,000	2,851,000	No data	UNSD, 2011
Wood Pellets	2,665	18	No data	No data	No data	UNSD, 2013
Wood Chips	201,701	104	No data	No data	No data	UNSD, 2013

A.3.3.3 Fuel Cost in India

Much of the population of India is extremely poor, which has a significant influence on the types of fuel used for cooking. Many of the poor are able to collect firewood, dung, or crop residues for free without traveling far from home.[80] They associate no cost with time spent gathering fuel, and so the users have a hard time giving up these “free” fuels.[81] However, firewood may be purchased within urban areas or in rural areas during the rainy season or due to local scarcities in some regions.

Fuels such as wood, crop residues, and dung are all less costly than the processed fuels available. Figure A-25 displays the cost on a basis of 2013 USD per person per year. Even when fuelwood is purchased, the cost to the consumer is commonly lower than cleaner burning fuels, such as LPG or crop residue briquettes. The cost of biogas from animal dung does include the initial capital cost of purchasing the digester and stove over the lifetime of the system. In the cases reviewed, the digester and stove are sold together, and so separating these costs were not possible. The cost analysis for biogas does not include costs associated with purchasing and maintaining livestock, as it is assumed that the livestock producing the dung are already owned by the household using the dung. The cost of non-carbonized briquettes from crop residues[82,83] is much higher than the costs of other fuels. In at least one instance, this was because increases in the cost of the crop residue feedstock were followed by a corresponding increase in the briquette cost, ultimately making the fuel cost more than (subsidized) LPG.[84] The cost of ethanol used specifically as a cooking fuel and costs for charcoal from wood or bamboo, wood pellets, and non-carbonized briquettes from wood are data gaps in this analysis.

LPG and kerosene fuels are subsidized by the Indian government. A quota of the kerosene fuel based on income is provided to those signed up for the subsidy program. The cost of kerosene at a market may be two or three times higher than the subsidized price.[85] The subsidy program for LPG provides a partial refund of the cost of the cylinders purchased directly to the consumer’s bank account.

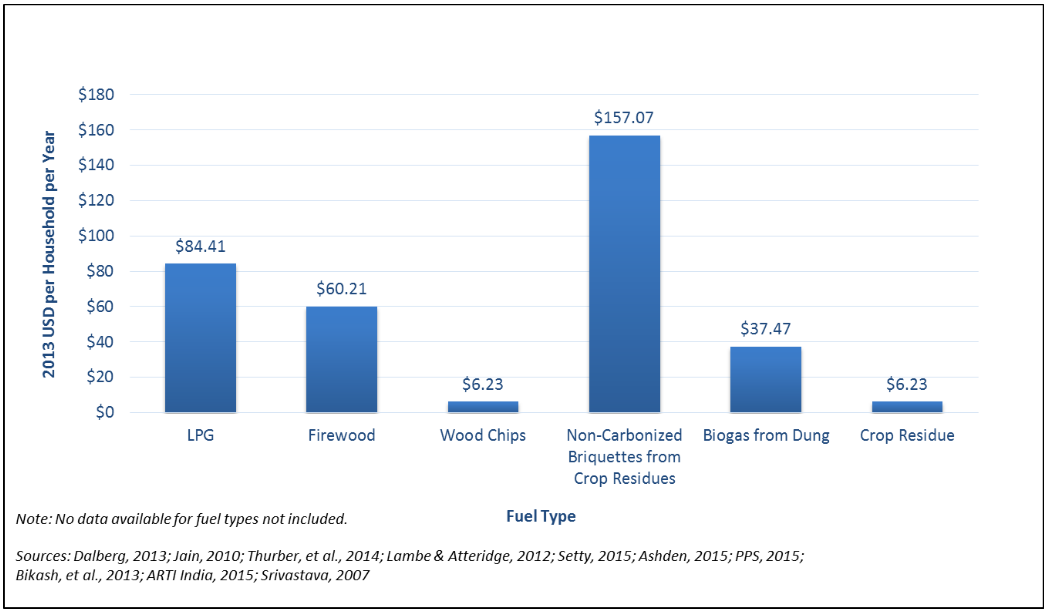


Figure A-25. Fuel Cost Indicator for Cooking Fuels in India

A.3.4 Social Indicators for India

Where possible, the social indicators are broken out by gender or by rural/urban discussions. Issues related to human health and exposure to cookstove emissions are not addressed. Complementary studies are underway or were completed through other initiatives within the cookstove sector.

A.3.4.1 Government Policies/Programs

The government of India aggressively promotes the use of LPG[86] at the household level by providing subsidies through its PAHAL Scheme. LPG cylinders purchased through participating oil companies are tracked and a partial refund credit is provided to the consumer's bank account for the number of cylinders purchased (with a maximum of nine cylinders per year).[87,88] The Scheme was recently modified and relaunched after reviewing issues consumers faced during its initial implementation, namely the requirement of a bank account opened with a government-issued identification (Aadhaar) number.[89] The updated Scheme launched in early 2015, and the subsidies have worked well in urban areas. Even with the subsidies, however, the poorest of the rural households are either unable or hesitant to purchase this fuel.[90] The revised Scheme was also rolled out with the "Give It Up" campaign, which requested that those households with the funds to pay for LPG without the subsidy not reenroll in the program. This campaign has been a success with over 1.3 million consumers voluntarily giving up their subsidy as of July, 2015.[91]

Government interventions in the LPG industry have also taken place at the state level. For example, in the late 1990s, the state government of Andhra Pradesh promoted the use of LPG in a program called the Deepam Scheme to reduce time spent gathering fuel, improve health by reducing exposure to smoke and emissions, and slow deforestation.[92] This program covered the cylinder connection fee for families below the poverty line. An assessment of this program a few years later found that it did facilitate the use of LPG by the rural poor, but only to a limited extent. Families had confined it to incidental uses, such as for boiling water or when the cost of firewood use was higher during the monsoon season.[93] The state government of Karnataka also promoted LPG as part of its plan (Swacha Grama Yojana) for increasing clean cookstove adoption in villages. The program—along with the World Bankfunded Jal Nirmal project—was instituted after the centrally-funded National Program for Improved Cookstoves was withdrawn in 2002.[94]

In addition to policies subsidizing and/or promoting LPG directly, a host of government initiatives at the national level have an indirect effect on the LPG industry. For instance, policies such as Pradhan Mantri Gram Sadak Yojana and the National Maritime Development Program, which seek to improve road connectivity and waterway efficiency, respectively, have the potential to facilitate access to LPG (and other alternative fuels) in more remote parts of India.[95] Other national efforts, such as the National Clean Energy Fund (established 2011) and the National Mission for Enhanced Energy Efficiency (ongoing as of 2013)—though not LPG-specific—provide funding and innovative financing options for clean energy projects and energy-efficient appliances. Governmental interest in the development of clean energy infrastructure is also reflected in the use of rural labor—hired under the Mahatma Gandhi National Rural Employment Guarantee Act—to construct community-level biogas facilities.

Other government initiatives such as the National Biomass Cookstoves Programme and the National Policy for Empowerment of Women have sought to increase adoption of improved cookstoves and raise awareness about solid fuel usage.[96,97] Indirectly supporting these efforts, as well as the LPG initiatives described above, is the national government's regulation of the kerosene industry through an income-based kerosene quota. The quota caps the kerosene supply below household demand, thus generating volatile informal markets[98] and potentially demand for alternative fuels.

A.3.4.2 Supply & Access Challenges

Having fuels readily available is a challenge for many of the poorer households in India. Some households have more than one cookstove that they use for different purposes, and they often require different fuel types. Such a configuration can provide increased reliability whereby one stove could be used as a backup if fuel for another cookstove is not available for a short period of time.

LPG is used mainly by the middle and upper classes in India and is commonly available through distributors in the cities. Unless there are supply shortages, LPG is readily available to the urban population. Some rural households do use cylinders of LPG, but normally in tandem with cheaper fuels.[99] LPG cylinders are less accessible in rural India and are usually large and heavy to transport from the nearest village. However, oil companies have expanded the distribution throughout the country using franchisees to sell the cylinders. The oil companies are also developing smaller cylinders that are cheaper and easier to distribute.

Generally, unprocessed wood, crop residues or dung used by the rural poor for their primary fuel are readily available. Dung is normally collected from cows owned by families and is reliably available as long as there is a sufficient number of livestock. The same is also true for the biogas produced from digesters using dung as feedstock, assuming proper use and maintenance of the system. Farming families who use their crop residues as fuel depend on their livelihood to provide reliable fuels for cooking. As long as they continue to farm and crops are not destroyed by drought, insects, or other natural disasters, crop residues for fuel use are available at no cost, except the time to collect it. The sustainability of firewood as a fuel source, however, is more of a concern. Some states in eastern India have reached levels of deforestation where the collection of firewood is detrimental to the environment. For example, Nagaland has lost almost 5 percent of its forest land since 2003.[100] Although afforestation efforts have gained some traction in aggregate—India has experienced an approximate 2 percent increase in forest land per year over recent years[101]—these effects have not been felt everywhere. Dalberg's 2013 market assessment found persistent deforestation in the east,[102] and efforts to restore India's biomass supplies elsewhere continue to face pressure from the demand for firewood. Driving this demand are the approximately 103 million people—predominately rural—who rely on collected firewood for around 90 percent of their cooking energy. Although those collecting firewood by hand are most vulnerable to biomass shortages, the approximately 60 million people who rely on purchased firewood[103] would also be affected by sustained losses in India's forestry sector.

Processed wood pellets, briquettes from wood, charcoal briquettes from wood, charcoal briquettes from bamboo, and briquettes from crop residues are all provided by small enterprises throughout India, though—like firewood—are presumably sensitive to unsustainable agroforestry practices. Briquettes are not as widely used in India,[104] but some sources are available in certain regions where these small enterprises are established. Wood pellets are more widely available than briquettes in India.[105] Pellets (from wood and from crop residues) are commonly used in both urban and rural settings. Supply chain consistency for these fuels is unknown and considered a data gap.

Ethanol is not a commonly used cooking fuel within India.[106] Its main use in India is as a transportation fuel. Some small enterprises are producing ethanol from sugarcane or from sawdust sources. The reliability of the supply chain for ethanol as a cooking fuel is dependent on regional availability and is considered a data gap.

A.3.4.3 Distribution & Adoption Challenges

The primary challenges to the distribution and use of nontraditional fuels in India relate to cost issues. With respect to both LPG[107] and biogas,[108] the transition—or start up—costs associated with switching to cleaner fuels are cited as prohibitive. For urban LPG users, smaller cylinders can make the transition more affordable, but more cylinders leads to more maintenance costs, and more frequent refills can lead to challenges if there is not a consistent supply chain.[109]

Rural, lower-income LPG users must not only pay for stoves and tanks (the latter, at times, can be rented), but also must often purchase LPG in bulk since the inaccessibility of remote markets prohibits more frequent smaller purchases.[110] Other issues associated with LPG use in rural environments include possible underfilling of the cylinders by distributors and dealing with the possibility that the distributor will not be at the fuel attainment point after traveling many kilometers to purchase the fuel.[111] As indicated in Figure A-25 above, upfront costs also factor in for potential biogas users, who must install a digester and purchase a compliant stove. What the cost in Figure A-25 does not reflect, however, is that users must also maintain enough livestock for the system to be cost-effective.[112] Given the variety of biogas systems available and that users of systems accepting animal dung also typically use other inputs such as distillery effluent and municipal waste,[113] it is difficult to approximate the quantity of livestock required for typical or optimal household-level biogas production in India.

Another factor affecting use of cleaner fuels in India is a lack of awareness of the costs and benefits of nontraditional fuels. Although knowledge of improved cookstoves and alternative fuels is lagging in India, the likelihood of adopting clean cooking methods and fuels increases with educational achievement, especially among women, who, when making decisions for the household, choose modern fuels such as LPG 43 percent of the time, compared to 29 percent across all households.[114,115,116,117] This finding suggests that awareness-raising programs[118] and initiatives aimed at enabling female decision makers could have a substantial impact on the adoption of clean cooking fuels. Such programs are likely to have the greatest traction in South India where women tend to have more influence on expenditures and household decision making than women in northern states such as Rajasthan and Uttar Pradesh, where marital status is more likely to dictate autonomy and empowerment.[119]

A final concern relates to taste preferences and the reluctance to move away from traditional cookstoves due to habit.[120] Dalberg's 2013 market assessment broke India down into five "food zones" based on preferences for staple foods. Although these categorizations are "meant to provide a high-level view only," they give a sense of regional variations in food choice and the traditional cooking equipment (all of which presumably use biomass) typically used to prepare them.

- North
  - Staple food – thick rotis (tandoori rotis, naan, paratha)
  - Equipment – kadhai (similar to a wok), tava (similar to a frying pan), smoke oven
  - Heat intensity – high

- Central
  - Staple food – thin rotis (roti, chapati)
  - Equipment – kadhai, tava
  - Heat intensity – medium-high

- East
  - Staple food – rice
  - Equipment – pots, kadhai, smokehouse
  - Heat intensity – medium

- West
  - Staple food – thick rotis (chapati, millet rolls)
  - Equipment – kadhai, tava
  - Heat intensity – medium-high

- South
  - Staple food – rice, dosa (rice pancake)
  - Equipment – pots, kadhai, tava
  - Heat intensity – medium-high

Clean cooking initiatives in these five "food zones" would benefit from promoting stoves and fuels that can supply adequate energy for preparing these staple foods. Although certain biases and attitudinal barriers may persist—for example, some people associate the taste of food cooked using LPG with "city life"[121]—underscoring the continuity of cooking options when marketing alternative fuels might improve the likelihood of adoption among some segments of the population.

A.3.4.4 Protection & Safety

Collection of dung and crop residues usually occurs somewhat close to the household, and no safety issues were found in literature. Collection of wood for fuel, however, can be perceived as dangerous if women or children collecting the wood must travel farther away from the village. In this case, the person collecting the fuel may experience aches, bruises,[122] or bites (presumably animal/insect)[123] while gathering the wood, and allergies, chapped hands, or limb deformation from chopping it.[124] Other repetitive stress injuries and complications follow from regularly carrying loads of 20-30 kgs of firewood on the head/shoulders, including head and spinal injuries, pregnancy complications, and maternal mortality.[125] Any of these issues could lead to serious medical complications in their own right and potentially social problems if household duties were interrupted. Gender-based violence and the potential for attacks also increase when women leave the safety of their communities,[126] leading to women and children sometimes collecting firewood in groups to stay safe from harassment.

For purchased fuels considered in this analysis (e.g., LPG, ethanol, briquettes), no safety issues during the purchase of the fuels were found within literature. However, concerns over potential burns from cooking incidents or gas leaks, due to negligence of cylinder maintenance, are associated with LPG use.

A.3.4.5 Time & Drudgery

Normally traditional fuels such as fuel wood, crop residues, and dung are gathered locally by women; however, in some regions that have scarce forest resources, men may take carts to collect fuel from longer distances. Children normally are not sent to remote locations but will collect branches close to the home.[127] Household-level collection time estimates for firewood range from 3 to 10 hours per week.[128,129,130,131,132,133] Estimates of time spent collecting dung or crop residues are somewhat lower, in the range of 3 to 5 hours per week.[134,135,136] It should be noted that a biogas system using dung will take time to install, plus time to add feedstock on a regular basis. The manual work involved in operating of the biogas plant is 10 man-hours/month.[137] Using purchased fuels, such as charcoal, briquettes, LPG, ethanol, or pellets, would reduce the time for acquiring fuels, freeing time for other tasks. These could include generating extra income, possibly by weaving or working on farms, to assist in paying for these fuels.[138] In other cases, this extra time could be used for social or family activities.[139] As an example of the time savings that are possible, one study found that time allocated to collecting traditional biomass decrease by approximately one-third (0.52 hours per day as opposed to 0.76 hours per day) when households also used LPG. [140]

There is also potential for time savings with respect to cooking over different fuels, and, since women and children bear the bulk of the cooking burden in India,[141] they would feel the most immediate reduction in time poverty if more efficient cooking methods were adopted. Cleaner fuel stoves using purchased fuels such as charcoal, pellets, and ethanol likely require less time than cooking over firewood due to heating values compared to traditional biomass stoves. Cooking with firewood takes approximately 2.5 hours per day, while cooking with raw dung and crop residues takes up to one half hour more due to lower heating values and burning efficiencies.[142] This estimate is in line with other studies,[143] which report 2.59 hours of cooking time per day using firewood, 2.82 hours using unprocessed dung and 3.01 hours per day using unprocessed crop residues. In contrast, a survey of women in rural regions states the cooking time as 5 hours per day.[144]

Alternatively, a survey of households adopting LPG found the fuel to decrease cooking time between 0.75 and 1.5 hours of cooking time/day, which lead to daily cooking times within a majority of the households surveyed of between 1-3 hours.[145] Information on time savings for use of other fuels in this study, such as charcoal briquettes, pellets, ethanol, and biogas, was not found. However, because these fuels burn more efficiently and have higher heating values than unprocessed biomass fuels commonly used, it is expected that these fuels will also save time while cooking. Moreover, time savings, in many cases, is also a proxy for fuel savings, and the transition to more efficient cooking methods could lead to substantial livelihood impacts. For example, one clean cookstove program in India found women were able to use money saved on fuel to provide their families with two meals per day instead of one.[146]

A.3.4.6 Income Earning Opportunities

LPG is one of the primary fuels used in India,[147] and there is potential for business viability, particularly for those developing smaller (and thus less costly) LPG cylinders.[148] The LPG market is growing at 2 percent per year,[149] so this fuel might afford greater income earning opportunities in the future.

Firewood is another commonly used fuel in India.[150] According to a survey in the mid-1990s, up to 70 percent of firewood is collected rather than purchased, but a gradual shift toward purchased firewood suggests that freely-available wood is becoming scarcer and there might be increasing commercial opportunities for firewood sellers.[151]

Other fuels, such as pellets and briquettes, are used by a small percentage of the population, but have had enough success to result in some income earning opportunities. These opportunities, however, are likely to remain small scale as corporations are reluctant to invest in biomass fuels.[152] Moreover, it is unclear if these employment opportunities have extended to women along with men.

A.3.4.7 Opportunities for Women Along the Value Chain

According to the Global Alliance for Clean Cookstoves 2013 Results Report, the clean cookstove industry currently has 252 employees (25% of whom are women) and 1,606 micro entrepreneurs (66% of whom are women).[153] However, there are currently no data available to estimate potential increases of skills for women with respect to specific fuels. It is known that NGOs, such as SEWA and TIDE, hold training for female entrepreneurs in the cookstove industry and employ women as door-to-door salespeople, but macro employment data are only available in aggregate.[154] 36 percent of women participate in the labor force overall, and only 19 percent participate in the organized sector (the rest participate in informal sectors such as cottage industries that are not tracked in national statistics). Of the women participating in the organized sector, 70 percent are employed by the government.[155]

Despite the inequalities in the national labor market, many small enterprises producing fuels in India are focused on encouraging women to join their groups in areas of sales, management, and even production in some cases. However, the LPG industry—potentially a site of great economic opportunity–seems to be a more male-oriented industry. While the LPG industry tried to encourage women's participation by instituting a condition that the wives of all dealers would be considered equal partners, in practice it is unknown if the women were actually involved in the distribution. Often times, a man used his wife's name to start a dealership with limited involvement from the woman.[156]

As illustrated with the LPG industry, there are substantial cultural barriers to female involvement in the clean cooking sector. In addition to the trend of husbands taking over businesses that require activity in the public sphere, women—particularly those interested in sales—must combat social constraints on female mobility (e.g., in some areas unmarried women are not allowed to travel around the community for commercial purposes) and the class-based stigma that only poor women engage in public retail activity.[157] Although not an issue in all communities, the caste system exacerbates some of these barriers. For example, caste dynamics might dissuade a higher-caste woman with access to resources from travelling to make sales to a part of the community where lower-caste women tend to live. Alternatively, a lower-caste saleswoman might have greater mobility, but less social capital with which to influence potential customers.[158]

A.4 Detailed Results for Bangladesh

A.4.1 Overview of Bangladesh

Bangladesh has the eighth largest population in the world.[159] Over 90 percent of the population is reliant on firewood, crop residues, or dung for their cooking fuel. Approximately 72 percent of the population lives in rural areas[160], and about 43 percent lives below the international poverty line, making Bangladesh among the poorest countries in the world.[161] As a result, fuel cost is an important concern. With the exception of kerosene[162], improved fuels are beyond the financial reach for many consumers. The Bangladesh Petroleum Corporation controls most of the dependable kerosene supply, including its relatively stable pricing system, which is generally uniform across the country in both rural and urban regions. Since access to local biomass is becoming more difficult due to deforestation, biomass fuels are becoming a marketed commodity.[163]

Bangladesh relies heavily on biomass, with firewood, crop residues, and dung used as a fuel source in 99 percent of homes in rural areas and in more than 60 percent of homes in urban areas.[164] Many of the lowest income people live in remote or ecologically fragile areas, which are vulnerable to natural disasters.[165] Each year, about 18 percent of the country's land area is flooded.[166] When rural households are unable to gather wood or crop residues during the rainy season, they may have to purchase fuels. Most households have two traditional-type stoves, one outside and one inside for use in the rainy season.[167] This is less common in cities, where gas and electric stoves can be found.[168] Many homes are small and do not have the space to store large amounts of fuels, which is one reason fuels must frequently be gathered or purchased in small amounts.

Adequate supply of fuel resources to sustainably support current or increasing levels of use is an important consideration. Bangladesh has shown an overall trend of an approximately 0.2 percent decrease in forest land per year over recent years,[169] although deforestation now appears to have been largely slowed or stopped through concentrated action by the government and its development partners.[170] Given the population's heavy reliance on wood fuels, as well as demand for wood for other uses, the sustainability of the wood supply remains a concern.

Finally, cultural issues related to food and cooking fires are an important consideration. Cooking habits are similar across Bangladesh, with rice as the mainstay for most meals and a need to cook large volumes of food in large pots. For cultural and historical reasons, families prefer fixed traditional stoves and use whatever type of biomass they can gather.[171] As observed in other countries, cooking fires may serve additional purposes in the home, such as providing heat or light. Changes to the cooking fuel or type of cookstove would likely require the household to use other fuels for these functions.[172]

The following sub-sections address the environmental, economic, and social considerations related to cooking fuels and stoves for Bangladesh in greater detail.

A.4.2 Environmental Indicators for Bangladesh

This section covers the detailed Bangladesh LCA results for the ten environmental indicators assessed for each fuel. The stove thermal efficiency by fuel and the fuel heating values employed in this study to calculate the LCA results are provided in Table A-27 and Table A-28, respectively. The remainder of this section presents results for each environmental indicator.

Table A-27. Stove Thermal Efficiency Applied by Fuel for Bangladesh

Fuel Type	Stove Thermal Efficiency	Sources
Firewood	13.5%	IEA, 2014
Charcoal Briquettes from Wood	17.5%	Singh et al., 2014
Charcoal Briquettes from Bamboo	17.5%	Singh et al., 2014
Non-Carbonized Briquettes from Sawdust	29.9%	GACC, 2015a Urban Uganda, 2015
Non-Carbonized Briquettes from Crop Residues	31.0%	GACC, 2015a
Wood Pellets	53.0%	Jetter et al., 2012
Wood Chips	31.0%	GACC, 2015a
Ethanol from Sugarcane	53.0%	Aprovecho Research Center, 2009
Ethanol from Wood	53.0%	Aprovecho Research Center, 2009
Biogas from Dung	55.0%	Singh et al., 2014
LPG	57.0%	Singh et al., 2014

Table A-28. Fuel Heating Values for Bangladesh

Fuel Type	HHV (MJ/kg)	Sources
Firewood	15.84	Singh et al., 2014
Charcoal Briquettes from Wood	27.86	Singh et al., 2014
Charcoal Briquettes from Bamboo	32.19	Singh et al., 2014 NMBA, 2005
Non-Carbonized Briquettes from Sawdust	18.6	Kaur et al., 2012 Grover et al., 1996 Davies et al., 2013 Vyas et al., 2015
Non-Carbonized Briquettes from Crop Residues	14.54	Vyas et al., 2015
Wood Pellets	17.94	Singh et al., 2014 Jetter et al., 2012
Wood Chips	15.84	Singh et al., 2014
Ethanol from Sugarcane	28.33	Aprovecho Research Center, 2009
Ethanol from Wood	28.33	Aprovecho Research Center, 2009
Biogas from Dung	18.2	Singh et al., 2014
LPG	53.37	Singh et al., 2014

A.4.2.1 Total Energy Demand

Table A-29 and Figure A-26 display the total energy demand impact results for fuels in Bangladesh by life cycle stage. Total energy demand sources consist of non-renewable fuels (natural gas, petroleum, coal, and nuclear) and "renewable" fuels (e.g. biomass, hydro). Energy demand tracks all energy inputs across the life cycle of the fuel, with energy impacts shown at the point of use of the relevant fuel.

The total energy demand results are largely a function of the fuel heating value and thermal efficiency of the fuel and stove combination (Table A-28 and Table A-27). Stoves with higher efficiencies (e.g., LPG, biogas, ethanol, and wood pellets) have a lower total energy demand overall, because more of the heating value of the fuel is converted into useful cooking energy and therefore less fuel must be produced, transported, and burned to deliver the same amount of cooking energy.

A number of observations can be made regarding energy results for the various types of fuels. For sugarcane ethanol, the feedstock energy results include not only the energy value of the sugar that is converted to ethanol but also the energy content of the bagasse, which provides the majority of energy used to process the sugarcane to molasses and then to ethanol. Wood ethanol energy demand impacts are lower than sugarcane since the wood residues are directly converted to ethanol; whereas, the sugarcane ethanol undergoes more agricultural and pre-processing steps to manufacture the ethanol end product. A co-benefit of ethanol production is the production of electricity, which may be exported. As discussed in the Appendix B methodology, this model employs the cut-off allocation methodology; therefore, a credit is not given here to the sugarcane or wood ethanol for exported electricity, so the energy demand impacts for ethanol should be considered as the upper bounds for these fuel types.

For non-carbonized wood fuels, the wood pellets and wood chips have a lower total energy demand than traditional firewood. Wood chips and wood pellets typically have a lower moisture content, greater energy content, and greater surface area than the traditional solid biomass, which allows the fuel to combust more efficiently. It is also more common to see improved cookstoves, which have higher stove thermal efficiencies, used in combination with the wood chips and wood pellets in Bangladesh.

For briquettes, the energy demand impact for the carbonized briquettes from wood and bamboo is relatively high compared to other fuels due to the lower stove efficiencies for metal charcoal briquette stoves in Bangladesh and the charcoal kiln energy impacts. That is, additional energy is consumed when burning firewood at the kiln to produce charcoal prior to charcoal utilization in a cookstove. All non-carbonized sawdust briquettes in Bangladesh are modeled as pressed manually and dried naturally to 10% moisture content. This requires 1.5 kg wood input to each 1 kg briquette, assuming a 40% moisture content of the original greenwood.[173]

Overall, liquid and gas fuels as well as processed solid biomass fuels not requiring additional combustion of solid fuel for processing (e.g., wood pellets) lead to the lowest overall total energy demand impacts.

Table A-29. Total Energy Demand (MJ) for Cooking Fuel Types (Bangladesh)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed solid biomass	Firewood	0	0	0	16,742	16,742
Processed solid biomass	Charcoal briquettes from wood	0	10,530	0.018	12,911	23,441
	Charcoal briquettes from bamboo	0	10,530	0.018	12,911	23,441
	Non-carbonized briquettes from sawdust	0	9,408	0.42	7,556	16,965
	Non-carbonized briquettes from crop residues	0	0	0.0028	6,733	6,733
	Wood pellets	0	1,011	0.25	4,139	5,150
	Wood chips	0	42.0	0.0058	7,296	7,338
Liquid/gas	Ethanol from sugarcane	440	9,954	6.77	4,263	14,663
	Ethanol from wood	0	102	0.071	4,684	4,787
	Biogas from dung	0	0	0	4,111	4,111
	LPG	61.1	574	104	3,964	4,702

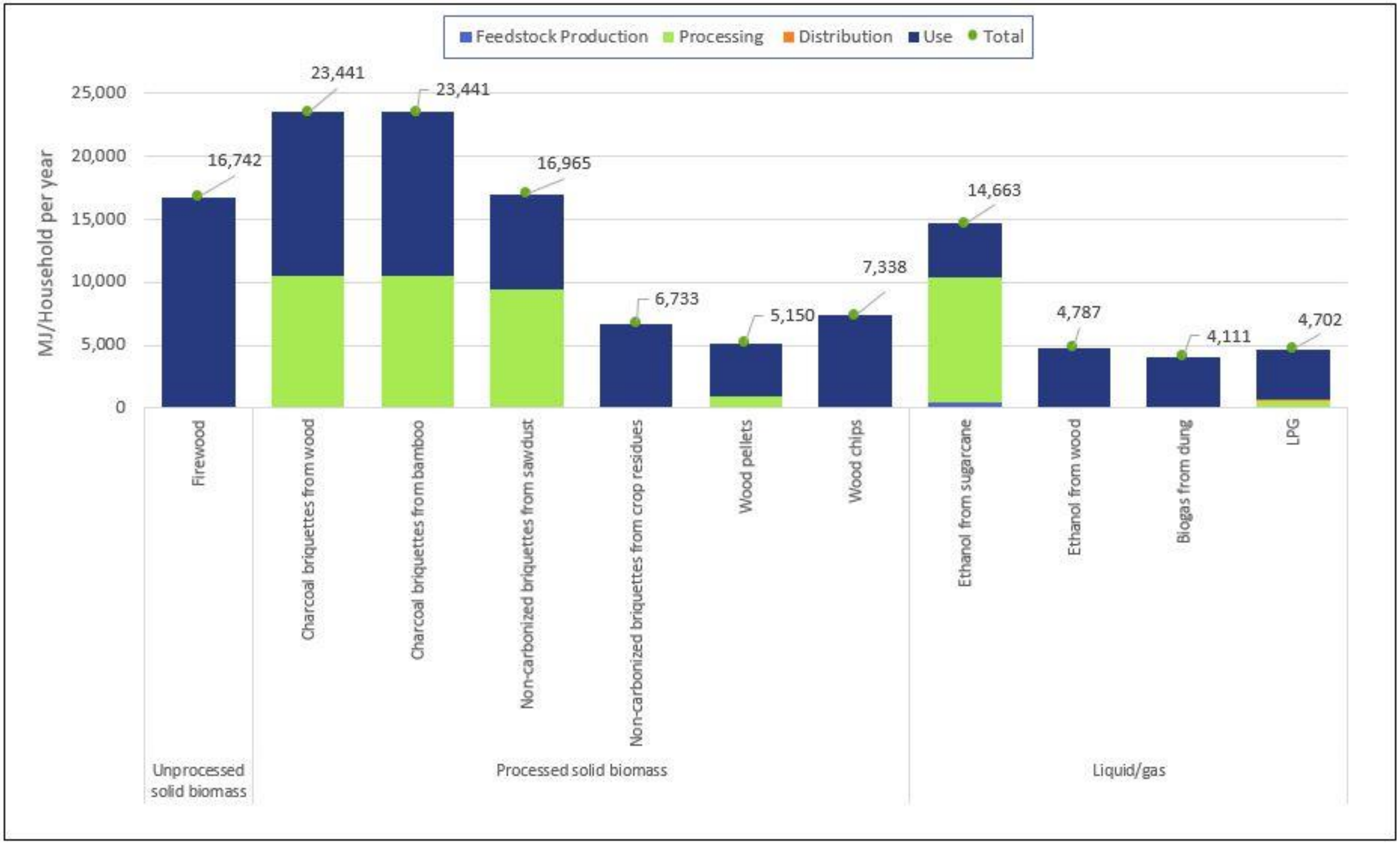


Figure A-26. Total Energy Demand (MJ) for Cooking Fuel Types (Bangladesh)

To produce, distribute and use cooking fuels by a single household per year

A.4.2.2 Net Energy Demand

Table A-30 and Figure A-27 illustrate the net energy demand impact results for fuels in Bangladesh by life cycle stage. Net energy demand is calculated in the same way as total energy demand, with the final energy delivered to the cooking pot deducted from the results. The net energy indicator is, therefore, the additional energy required for the life cycle of the cookstove fuel beyond what is delivered to the consumer for cooking purposes. For Bangladesh, 6.19 MJ of cooking energy are consumed per household per day, which equates to 2,259 MJ per household per year.[174] Utilization of unprocessed solid biomass (i.e. firewood) consumes approximately seven times more energy than is provided to the pot, as listed in the last column of Figure A-31. Similar levels of net energy demand are seen for charcoal briquettes, non-carbonized briquettes from sawdust, and ethanol from sugarcane. The lowest overall net energy demand is calculated for non-carbonized briquettes from crop residues, wood pellets, wood chips, ethanol from wood, biogas from dung, and LPG. Production, processing, distribution, and use of these less energy intensive fuels uses 0.82 to 2.25 times the amount of energy delivered to the pot.

Table A-30. Net Energy Demand (MJ) for Cooking Fuel Types (Bangladesh)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total	Net Energy Consumed: Delivered Energy
		Feedstock Production	Processing	Distribution	Use		
Unprocessed solid biomass	Firewood	0	0	0	14,483	14,483	6.41
Processed solid biomass	Charcoal briquettes from wood	0	10,530	0.018	10,651	21,182	9.38
	Charcoal briquettes from bamboo	0	10,530	0.018	10,651	21,182	9.38
	Non-carbonized briquettes from sawdust	0	9,408	0.42	5,297	14,706	6.51
	Non-carbonized briquettes from crop residues	0	0	0.0028	4,474	4,474	1.98
	Wood pellets	0	1,011	0.25	1,880	2,890	1.28
	Wood chips	0	42.0	0.0058	5,036	5,078	2.25
Liquid/gas	Ethanol from sugarcane	440	9,954	6.77	2,004	12,404	5.49
	Ethanol from wood	0	102	0.071	2,425	2,528	1.12
	Biogas from dung	0	0	0	1,852	1,852	0.82
	LPG	61.1	574	104	1,704	2,443	1.08

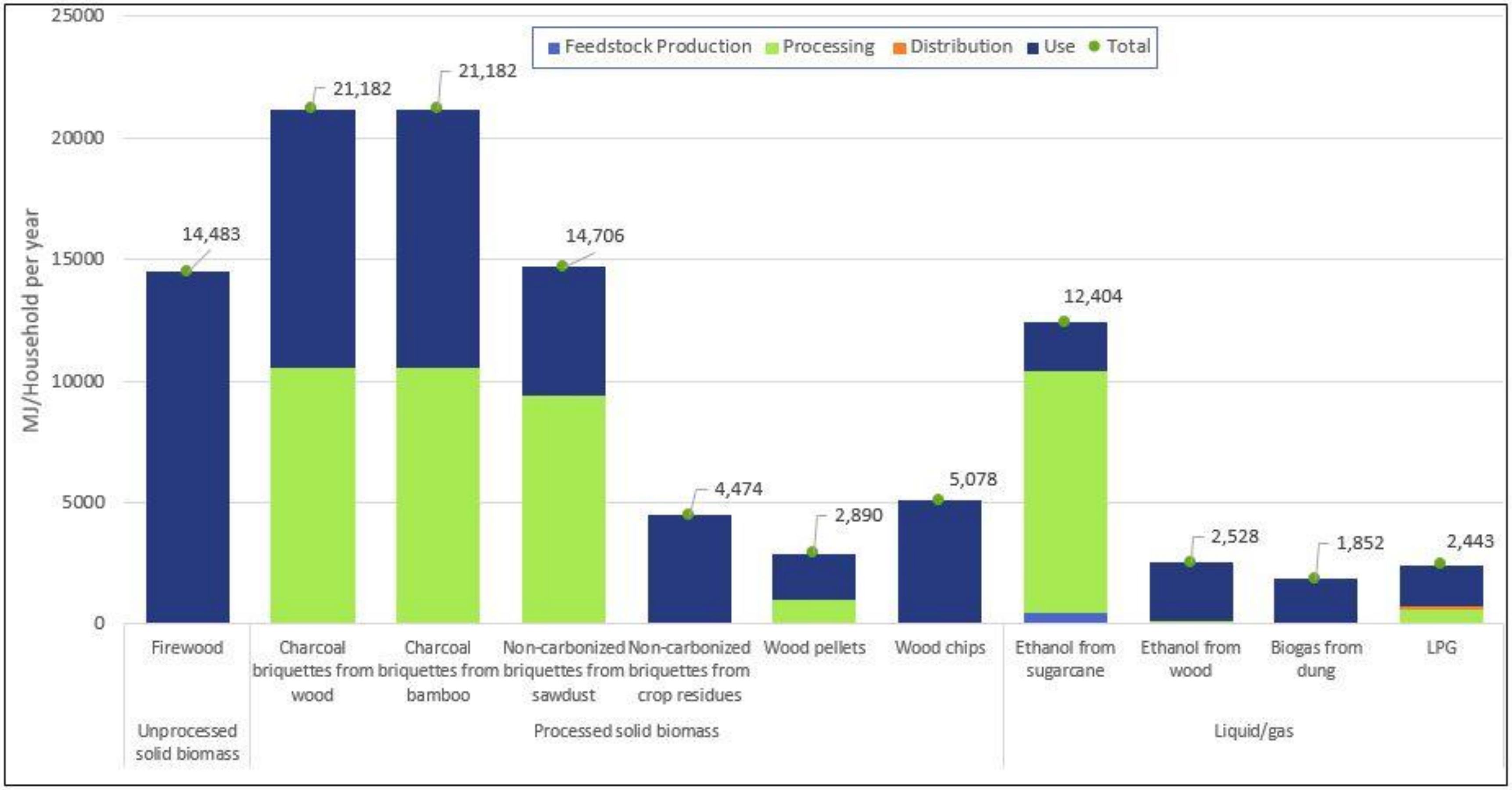


Figure A-27. Net Energy Demand (MJ) for Cooking Fuel Types (Bangladesh)
To produce, distribute and use cooking fuels by a single household per year

A.4.2.3 Global Climate Change Potential

Table A-31 and Figure A-28 present the global climate change potential (GCCP) impact results for fuels in Bangladesh by life cycle stage. The GCCP impact category represents the heat trapping capacity of greenhouse gases over a 100 year time horizon. Fossil fuel GCCP impacts are dominated by combustion emissions in the cookstove use stage.

Biogas GCCP impacts are primarily from methane leakage during the production of biogas in an anaerobic digester. Sugarcane ethanol, charcoal briquettes from bamboo, and briquettes from crop residues are derived from renewable biomass that removed CO_2 from the atmosphere during growth; therefore, the CO_2 emissions released from combustion of these fuels is considered carbon neutral, as discussed in detail in the Appendix B methodology. Impacts for these renewable fuels during the use phase are driven by nitrous oxide and methane emissions during cookstove use. Impacts associated with fertilizer production and emissions from application also play a role in the sugarcane ethanol overall impacts.

Based on the decreasing trend in forest area in Bangladesh, all of the wood harvested for use as cooking fuel is considered unsustainably sourced, and the combustion emissions for the non-sustainable use of wood are not considered carbon-neutral. This adjustment is also applied to other wood fuels (wood-derived charcoal briquettes, wood pellets and wood chips), but not to fuels derived from wood wastes (wood ethanol and non-carbonized briquettes from sawdust). With the cut-off modeling methodology used in this analysis, wood wastes are treated as a “free” product (all burdens are allocated to the primary wood product, e.g., lumber, which is outside the scope of this study), so emissions of biomass CO_2 for fuels derived from wood waste are treated as carbon neutral. For charcoal briquettes, GCCP impacts for carbonization of the wood in the kiln are comparable in magnitude to the emissions from combustion of the charcoal briquettes in a cookstove. Charcoal kiln impacts are largely driven by the methane emissions during the carbonization process. Combustion emissions for bamboo-derived charcoal briquettes are lower than for wood-derived charcoal briquettes because bamboo is a renewable crop and all combustion emissions are considered carbon-neutral, while none of the wood combustion emissions are considered carbon-neutral, since the wood supply in Bangladesh is considered non-renewable based on the decreasing forest area. All GHGs associated with the production and combustion of LPG, including CO_2 emissions from cooking, are considered fossil-derived and accounted for in the GCCP impacts.

Table A-31 Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (Bangladesh)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total
		Feedstock Production	Processing	Distribution	Use	
Unprocessed Solid Biomass	Firewood	0	0	0	1,875	1,875
Processed Solid Biomass	Charcoal Briquettes from Wood	0	907	31.1	1,341	2,279
	Charcoal Briquettes from Bamboo	0	335	31.1	104	470
	Non-Carbonized Briquettes from Sawdust	0	0	31.2	173	204
	Non-Carbonized Briquettes from Crop Residues	0	0	0.21	103	103
	Wood Pellets	0	67.5	18.5	775	860
	Wood Chips	0	3.35	0.43	816	820
Liquid/Gas	Ethanol from Sugarcane	180	11.9	0.48	2.16	195
	Ethanol from Wood	0	11.1	5.28	2.16	18.5
	Biogas from Dung	0	20.8	0	2.99	23.8
	LPG	10.4	34.2	7.11	619	671

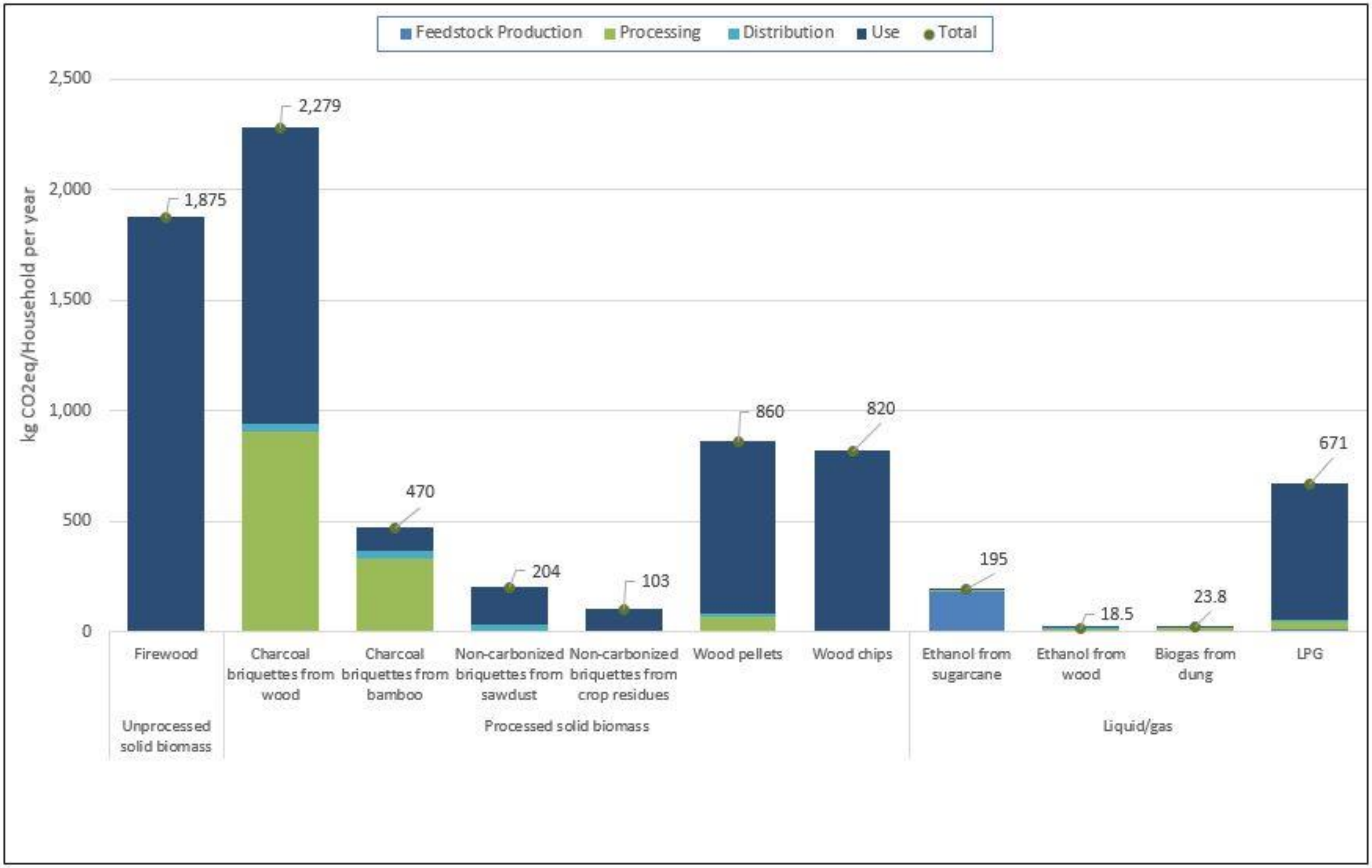


Figure A-28. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (Bangladesh)
To produce, distribute and use cooking fuels by a single household per year

A.4.2.4 Black Carbon and Short-Lived Climate Pollutants

Table A-32 and Figure A-29 display the black carbon and short-lived climate pollutants impact results for fuels in Bangladesh by life cycle stage. Black carbon (BC) is formed by incomplete combustion of fossil and bio-based fuels. BC is the carbon component of particulate matter (PM) with aerodynamic diameter less than or equal to 2.5 microns (PM2.5). This is the size of PM that most strongly absorbs light and thus has potential radiative forcing effects (i.e., potential to contribute to global warming). Potential climate forcing impacts resulting from BC emissions include direct, albedo (i.e., fraction of solar energy hitting the earth that is reflected), and other effects. BC is emitted with other particles (e.g. organic carbon) and criteria pollutants such as nitrogen and sulfur dioxides. Though some of these co-pollutants may exert a cooling effect on climate, the net effects of BC emissions likely contribute to global climate warming. Appendix B shows the 20 year global warming potential and black carbon equivalent values used in the results calculation. Results are presented here based on BC equivalents. The highest BC impacts are seen for traditional unprocessed biomass fuels as well as charcoal and non-carbonized briquettes, which tend to have high particulate matter emissions when combusted. Similarly, high emissions of particulate matter are seen in the charcoal kiln, which combusts wood to carbonize the fuel. Utilization of the liquid and gas fuels result in the lowest overall BC impacts. Some life cycle stages, for instances those related to sugarcane ethanol and LPG, have negative BC equivalent impacts, which is the case when emissions of SO_x and organic carbon, pollutants with net cooling effects on the climate, are greater than the emissions of BC and other co-emitted pollutants that lead to short term warming impacts.

Table A-32. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (Bangladesh)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	1.70	1.70
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.70	0.0021	0.58	1.28
	Charcoal Briquettes from Bamboo	0	0.70	0.0021	0.58	1.28
	Non-Carbonized Briquettes from Sawdust	0	0	0.0021	1.20	1.20
	Non-Carbonized Briquettes from Crop Residues	0	0	1.4E-05	1.90	1.90
	Wood Pellets	0	-0.0030	0.0012	0.047	0.045
	Wood Chips	0	7.9E-04	2.9E-05	0.74	0.74
Liquid/Gas	Ethanol from Sugarcane	-0.0039	-0.016	-2.6E-04	0.0063	-0.014
	Ethanol from Wood	0	0.0037	3.5E-04	0.0063	0.010
	Biogas from Dung	0	0	0	0.015	0.015
	LPG	0.0013	-0.0082	-0.0027	0.012	0.0028

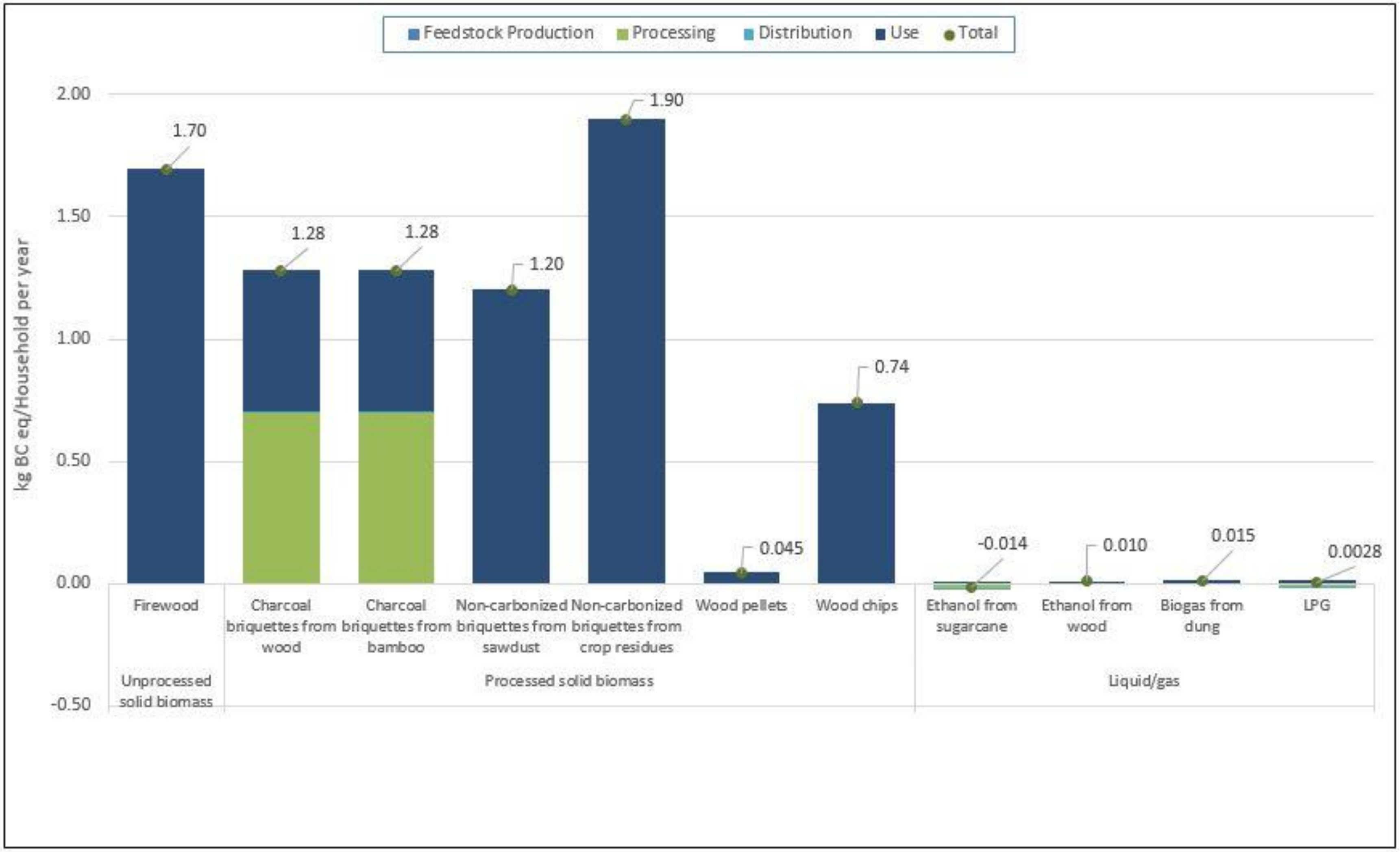


Figure A-29. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (Bangladesh)
To produce, distribute and use cooking fuels by a single household per year

A.4.2.5 Particulate Matter Formation Potential

Table A-33 and Figure A-30 show the particulate matter formation impact results for fuels in Bangladesh by life cycle stage. Particulate matter can contribute to many negative health impacts such as effects on breathing and respiratory systems, damage to lung tissue, cancer, and premature death. Primary and secondary pollutants leading to particulate matter formation as well as PM2.5 are characterized here to kg PM10 eq. Firewood and briquettes (carbonized and non-carbonized) lead to the greatest particulate matter formation impacts. Most particulate matter formation impacts occur during cookstove use at the household with the exception of charcoal briquettes, where the carbonization of the wood in the kiln dominates the overall life cycle impacts. LPG, ethanol as well as biogas and wood pellets have comparably small particulate matter impacts.

Table A-33. Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (Bangladesh)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	6.84	6.84
Processed Solid Biomass	Charcoal Briquettes from Wood	0	1.06	0.0539	1.57	2.69
	Charcoal Briquettes from Bamboo	0	1.06	0.0539	1.57	2.69
	Non-Carbonized Briquettes from Sawdust	0	0	0.0540	4.86	4.92
	Non-Carbonized Briquettes from Crop Residues	0	0	0	8.86	8.86
	Wood Pellets	0	0.0432	0.0320	0.233	0.31
	Wood Chips	0	0.013	7.5E-04	2.98	2.99
Liquid/Gas	Ethanol from Sugarcane	0.2576	0.079	3.5E-03	0.0010	0.34
	Ethanol from Wood	0	0.1371	9.1E-03	0.0010	0.15
	Biogas from Dung	0	0	0	0.175	0.17
	LPG	0.0256	0.0632	0.0360	0.135	0.26

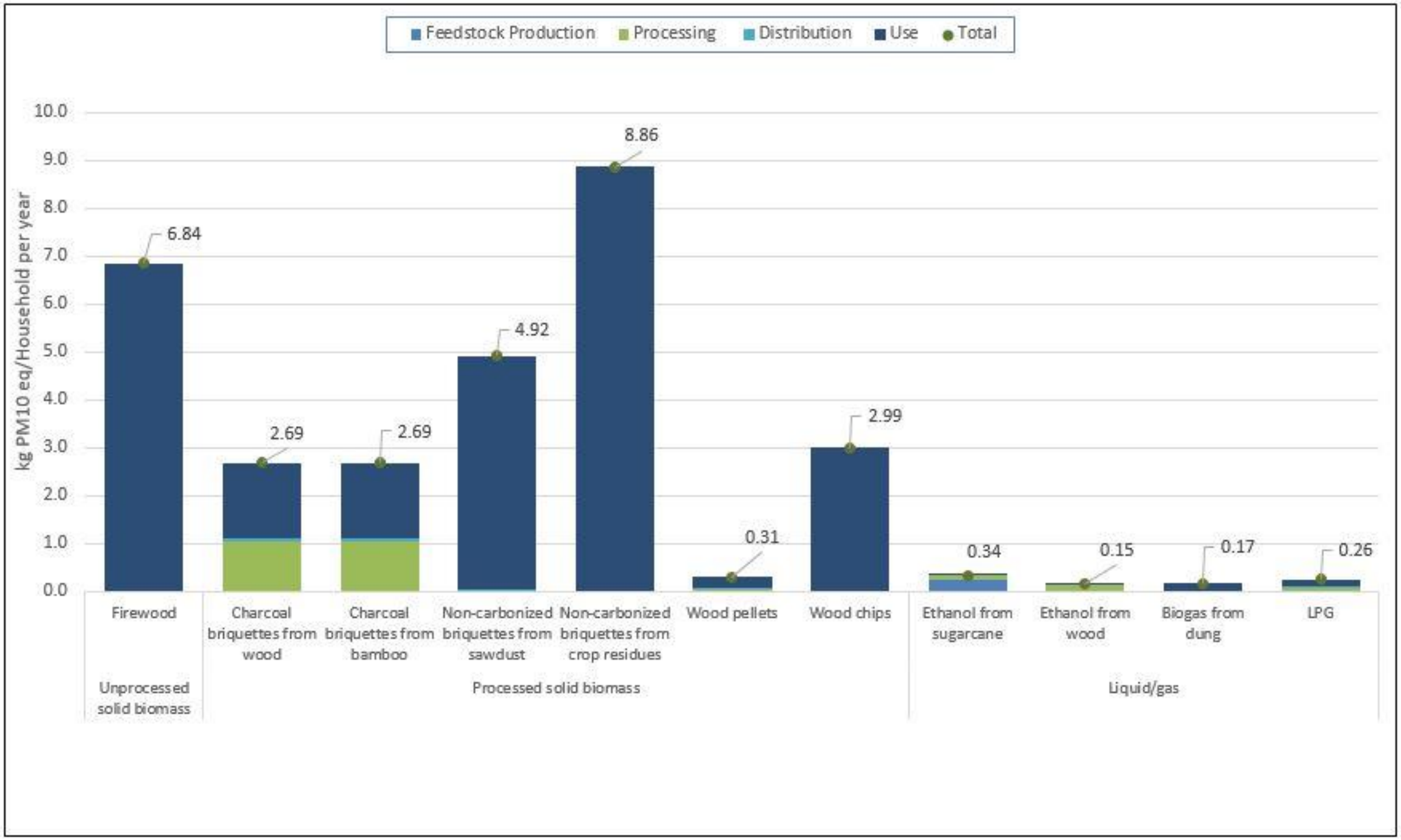


Figure A-30. Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (Bangladesh)
To produce, distribute and use cooking fuels by a single household per year

A.4.2.6 Fossil Fuel Depletion

Table A-34 and Figure A-31 provide the fossil fuel depletion impact results for fuels in Bangladesh by life cycle stage. Fossil depletion captures the consumption of fossil fuels, primarily coal, natural gas, and crude oil. All fuels are normalized to kg oil eq based on the heating value of the fossil fuel relative to the heating value of a kg of oil. The fossil depletion associated with firewood as well as biogas and ethanol from wood is negligible, as these fuels are not derived from fossil fuel, and collection of these fuels is done manually. While biomass fuels are not derived from fossil fuels, some fossil fuels may be consumed across the life cycle of these fuels for energy inputs to fuel production and processing, distribution, and disposal. Fossil depletion for wood pellets is associated with electricity usage for pelletization and some transport, while sugarcane ethanol fossil depletion is primarily from fertilizers during cane production, as well as diesel for farm operation and distribution of the feedstock and fuel. Some fossil depletion impacts are also seen for processing the wood chips for the portions of these fuels that are not processed manually (as discussed in detail in Appendix B 47% of wood chipping is modeled as mechanized in Bangladesh). Fossil depletion impacts are highest for LPG as this source of energy relies on fossil fuels.

Table A-34. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (Bangladesh)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total
		Feedstock Production	Processing	Distribution	Use	
Unprocessed solid biomass	Firewood	0	0	0	0.015	0.015
Processed solid biomass	Charcoal briquettes from wood	0	0.012	0.010	0.014	0.036
	Charcoal briquettes from bamboo	0	0.012	0.010	0.035	0.057
	Non-carbonized briquettes from sawdust	0	0	0.010	0.0080	0.018
	Non-carbonized briquettes from crop residues	0	0	6.7E-05	0.0059	0.0060
	Wood pellets	0	22.2	0.0060	4.1E-04	22.2
	Wood chips	0	1.00	1.4E-04	0.0063	1.01
Liquid/gas	Ethanol from sugarcane	27.5	6.32	0.16	0	34.0
	Ethanol from wood	0	2.41	0.0017	0	2.42
	Biogas from dung	0	0	0	0	0
	LPG	1.45	13.6	2.45	93.8	111

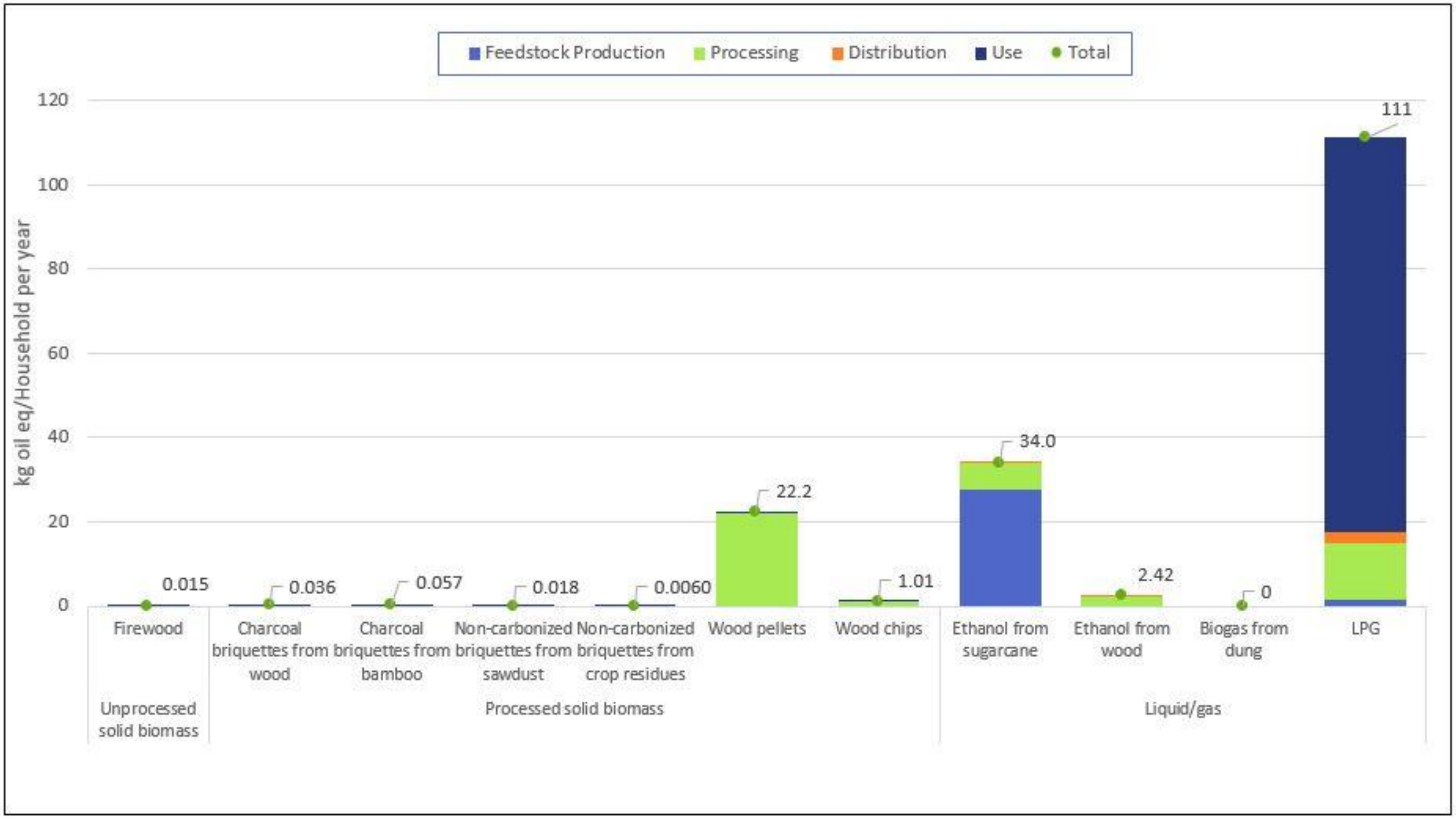


Figure A-31. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (Bangladesh)
To produce, distribute and use cooking fuels by a single household per year

A.4.2.7 Water Depletion

Table A-35 and Figure A-32 illustrate the water depletion impact results for fuels in Bangladesh by life cycle stage. Water depletion results are based on the volume of fresh water inputs over the life cycle of the assessed fuels. Water may be incorporated in the fuel product, evaporated, or returned to the same or different water body or to land. If the water is returned to the same water body, it is assumed the water is returned at a degraded quality, and therefore is considered consumptive use. Water consumption includes evaporative losses from establishment of hydroelectric dams but does not include the water passing through the turbine, since that water is not removed from its source. The hydropower in the electricity mix drives the overall water depletion impacts. Water depletion associated with wood pellets is due to electricity usage during pelletization/briquetting. Water depletion impacts are also notable for sugarcane ethanol, as irrigation is required for the cane production. Some water depletion impacts are also seen for the biogas to maintain the digester, but these are negligible when compared to the evaporative losses from hydropower in the electricity grid. Water depletion impacts are negligible for the traditional biomass fuel (i.e. firewood) and briquettes, which are not irrigated and processed manually (as is the case for the briquettes). Because the water content of these fuels comes from the atmosphere as rainfall, the water released back to the atmosphere when the biomass is dried or combusted is not considered consumptive use.

Table A-35. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (Bangladesh)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	0.11	0.11
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.093	9.5E-05	0.11	0.20
	Charcoal Briquettes from Bamboo	0	0.093	9.5E-05	0.11	0.20
	Non-Carbonized Briquettes from Sawdust	0	0	9.7E-05	0.061	0.061
	Non-Carbonized Briquettes from Crop Residues	0	0	6.4E-07	0.046	0.046
	Wood Pellets	0	15.8	5.7E-05	0.0020	15.8
	Wood Chips	0	1.04	1.3E-06	0.049	1.08
Liquid/Gas	Ethanol from Sugarcane	125	30.2	0.093	0	155
	Ethanol from Wood	0	0.63	1.6E-05	0	0.63
	Biogas from Dung	0	2.36	0	0	2.36
	LPG	4.46	38.8	1.45	0	44.7

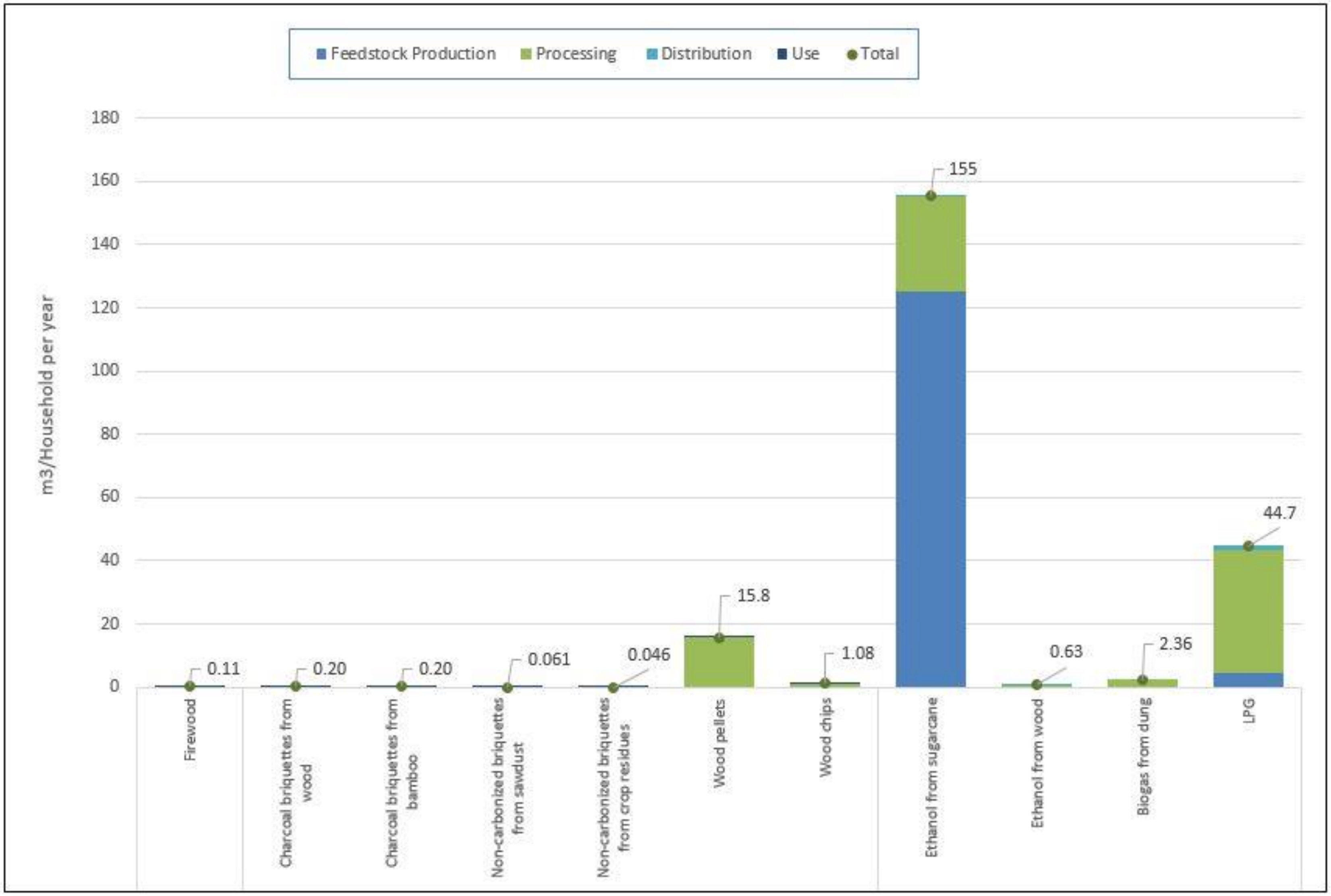


Figure A-32. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (Bangladesh)

To produce, distribute and use cooking fuels by a single household per year

A.4.2.8 Terrestrial Acidification Potential

Table A-36 and Figure A-33 show the terrestrial acidification potential impact results for fuels in Bangladesh by life cycle stage. Terrestrial acidification quantifies the acidifying effect of substances on their environment. Important contributing emissions include SO_2, NO_x, and NH_3. Electricity usage for pelletization drives wood pellet acidification impacts. Ethanol contains no sulfur, so there are no sulfur dioxide emissions, a main cause of acidification, for the ethanol cookstove use stage, although upstream impacts are seen for cane production and ethanol manufacture. Firewood has noticeably higher acidification impacts than the liquid and gas fuels. The main contributing emissions leading to acidification potential for firewood are SO_x and NO_x. For instance, NO_x leads to 48% and SO_x leads to 52% of the firewood acidification impacts, respectively. Distribution acidification impacts in Bangladesh are highest for transportation of the carbonized and non-carbonized briquettes since a greater mass of input fuel for the solid biomass is required to be transported a longer distance given the proximity of end users to forests in Bangladesh (Appendix B provides detailed discussions of the model’s transportation parameters). The lowest overall acidification impacts are seen for biogas. Because land applied digested sludge from biogas production is used by another product system, it is considered to be outside the system boundaries for this analysis; however, it is possible that this land applied digested sludge could lead to emissions of ammonia, an acidifying substance.

Table A-36. Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (Bangladesh)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	**Processing**	**Distribution**	**Use**	**Total**
Unprocessed Solid Biomass	Firewood	0	0	0	3.55	3.55
Processed Solid Biomass	Charcoal Briquettes from Wood	0	2.5E-04	0.13	0.46	0.59
	Charcoal Briquettes from Bamboo	0	2.5E-04	0.13	0.46	0.59
	Non-Carbonized Briquettes from Sawdust	0	0	0.13	1.91	2.04
	Non-Carbonized Briquettes from Crop Residues	0	0	8.6E-04	0.48	0.48
	Wood Pellets	0	0.14	0.077	0.076	0.29
	Wood Chips	0	0.026	0.0018	1.55	1.57
Liquid/Gas	Ethanol from Sugarcane	0.69	0.34	0.011	0	1.05
	Ethanol from Wood	0	0.16	0.022	0	0.19
	Biogas from Dung	0	0	0	0.24	0.24
	LPG	0.055	0.23	0.12	0.26	0.66

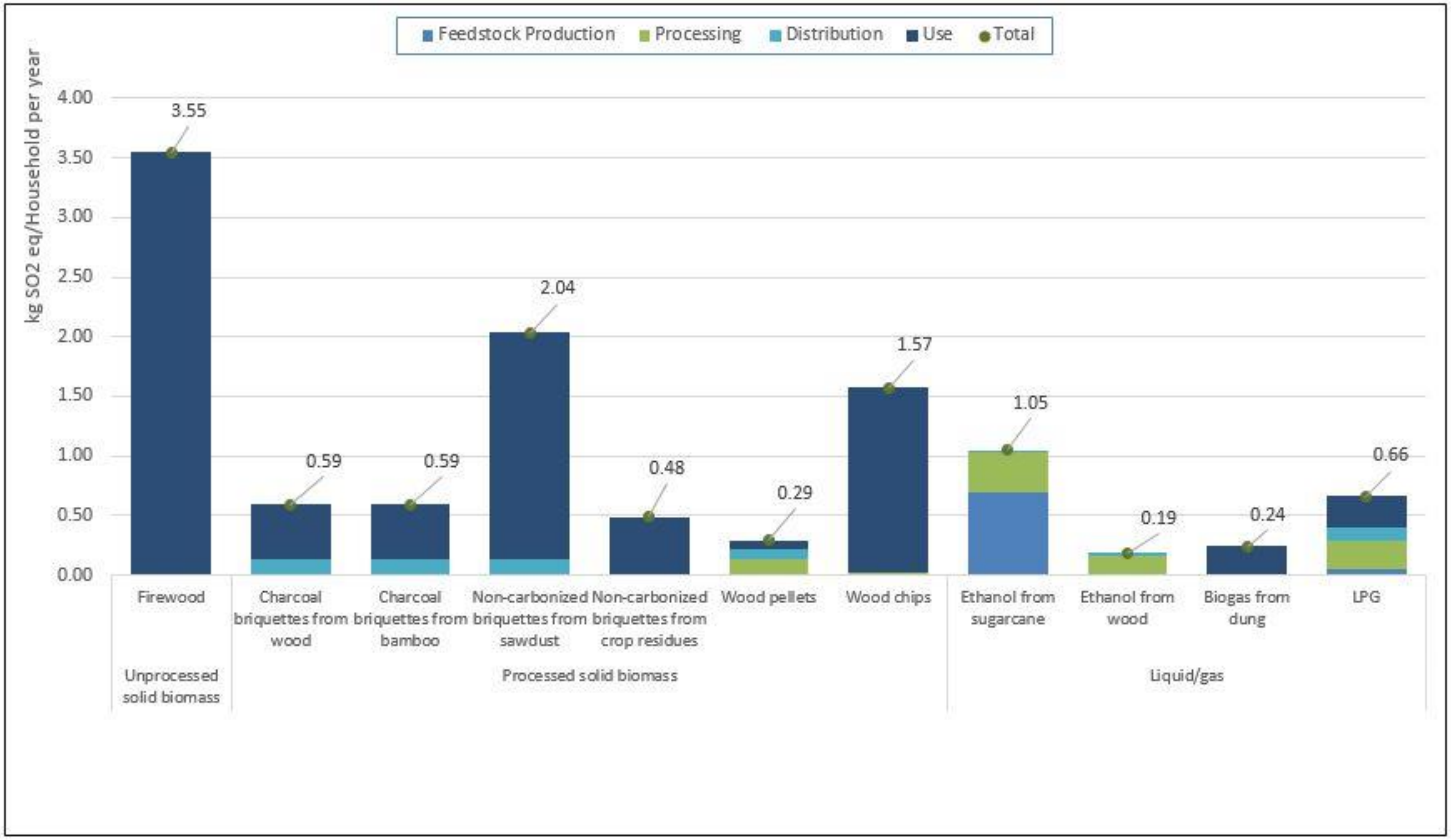


Figure A-33. Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (Bangladesh)

To produce, distribute and use cooking fuels by a single household per year

A.4.2.9 Freshwater Eutrophication Potential

Table A-37 and Figure A-34 provide the freshwater eutrophication potential impact results for fuels in Bangladesh by life cycle stage. Eutrophication assesses the impacts from excessive load of macro-nutrients to the environment and eventual deposition in freshwater, which can result in algal blooms, oxygen depletion, and fish kills. Pollutants contributing to this category are all P based (e.g. phosphate, phosphoric acid, phosphorus). Firewood and charcoal briquettes (from both wood and bamboo) result in the highest eutrophication potential impacts. This is due to the much larger ash quantity produced from firewood, including firewood to provide energy for a charcoal kiln, compared to all other fuels. The ash from the firewood, which contains phosphorus is assumed to be land applied, which leads to soil emissions and eventual runoff into freshwater. While impacts are comparably smaller for ethanol, there are some eutrophication impacts occurring from use of phosphorus based fertilizer in sugarcane production. There are no eutrophication impacts associated with biogas. Application of the digested sludge from the biogas system would likely lead to some eutrophication impacts, but utilization of this useful co-product is outside the system boundaries of this study. The digested sludge impacts are allocated to the product system it serves (i.e. nutrients for crop production). Impacts from fossil based fuels and biomass pellets are minimal compared to firewood and charcoal briquettes. The non-carbonized processed biomass fuels have slightly lower eutrophication potential impacts than traditional unprocessed biomass fuels and charcoal briquettes. Because processed biomass burns more efficiently than unprocessed biomass, less fuel must be burned, leading to an overall lower quantity of ash produced.

Table A-37. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (Bangladesh)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total
		Feedstock Production	Processing	Distribution	Use	
Unprocessed Solid Biomass	Firewood	0	0	0	0.37	0.37
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.30	1.1E-07	0.34	0.64
	Charcoal Briquettes from Bamboo	0	0.30	1.1E-07	0.34	0.64
	Non-Carbonized Briquettes from Sawdust	0	0	1.1E-07	0.20	0.20
	Non-Carbonized Briquettes from Crop Residues	0	0	7.4E-10	0.15	0.15
	Wood Pellets	0	9.3E-04	6.6E-08	0.0064	0.0073
	Wood Chips	0	1.5E-04	1.5E-09	0.16	0.16
Liquid/Gas	Ethanol from Sugarcane	0.075	0.0048	1.3E-05	2.4E-06	0.079
	Ethanol from Wood	0	5.0E-06	1.9E-08	2.4E-06	7.4E-06
	Biogas from Dung	0	0	0	0	0
	LPG	6.3E-04	0.0049	1.6E-04	0	0.0056

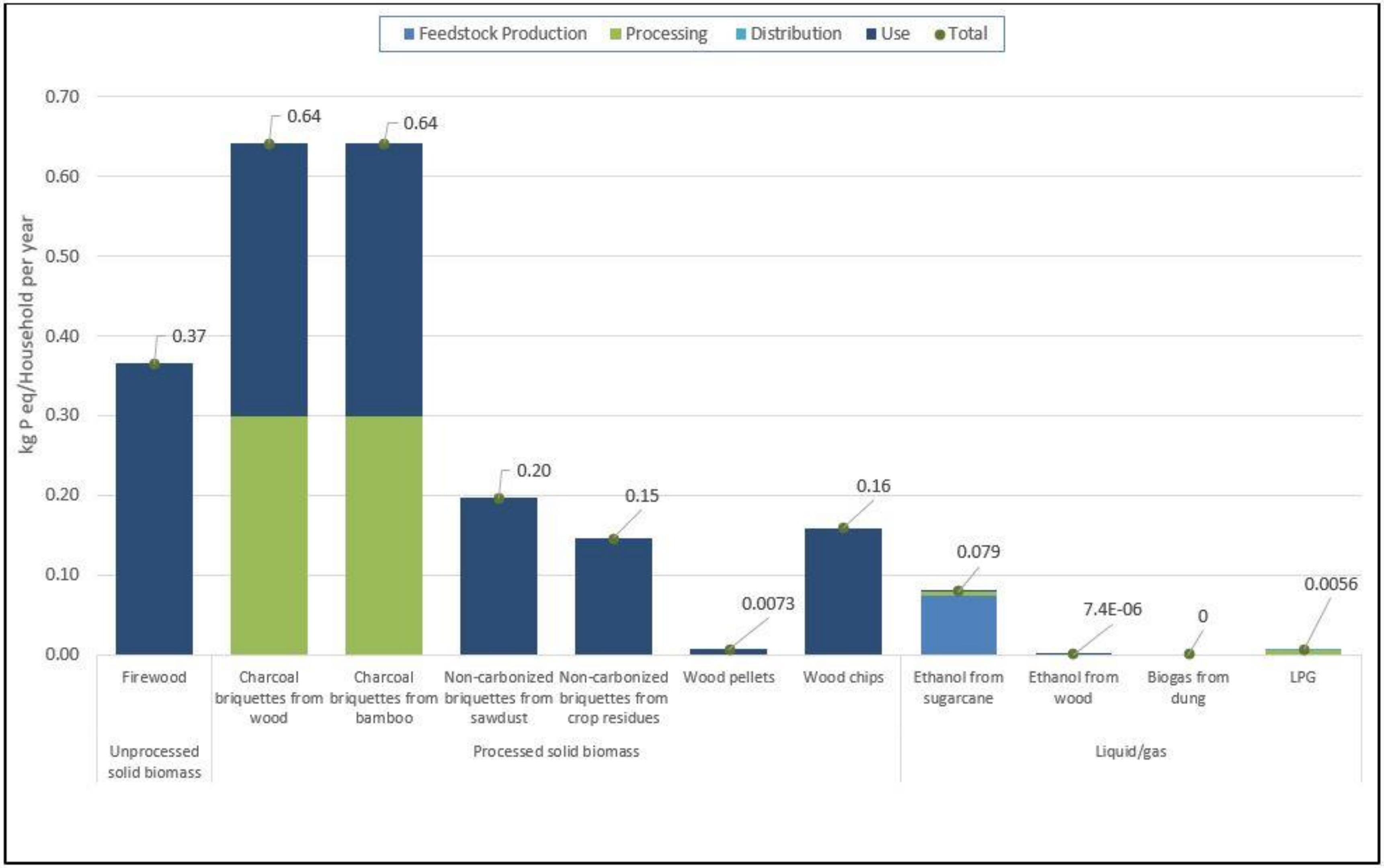


Figure A-34. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (Bangladesh)
To produce, distribute and use cooking fuels by a single household per year

A.4.2.10 Photochemical Oxidant Formation Potential

Table A-38 and Figure A-35 present the photochemical oxidant formation potential impact results for fuels in Bangladesh by life cycle stage. The photochemical oxidant formation (i.e. smog formation) results are an indicator of the potential for formation of reactive substances that cause harm to human health and vegetation. Results are characterized here to kg of non-methane volatile organic compounds (NMVOC) eq. Some key emissions for cookstove fuel systems that contribute to photochemical oxidant formation include carbon monoxide, methane, nitrogen oxides, NMVOCs, and sulfur dioxide. Charcoal briquettes, followed by processed wood fuels, lead to the greatest photochemical formation impacts. For charcoal briquettes, impacts are split between the fuel processing stage (carbonization in a kiln) and the use stage. Photochemical oxidant formation impacts are relatively small for the liquid fuels, processed non-carbonized biomass and biogas.

Table A-38. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (Bangladesh)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	8.96	8.96
Processed Solid Biomass	Charcoal Briquettes from Wood	0	49.8	0.22	11.4	61.4
	Charcoal Briquettes from Bamboo	0	49.8	0.22	11.4	61.4
	Non-Carbonized Briquettes from Sawdust	0	0	0.22	39.1	39.3
	Non-Carbonized Briquettes from Crop Residues	0	0	0.0015	6.86	6.86
	Wood Pellets	0	0.27	3.6E-06	0.23	0.50
	Wood Chips	0	0.044	0.0030	26.0	26.1
Liquid/Gas	Ethanol from Sugarcane	0.38	0.11	0.0087	0.14	0.64
	Ethanol from Wood	0	0.28	0.038	0.14	0.46
	Biogas from Dung	0.0083	0	0.25	0.26	0.51
	LPG	0.11	0.13	0.093	1.14	1.48

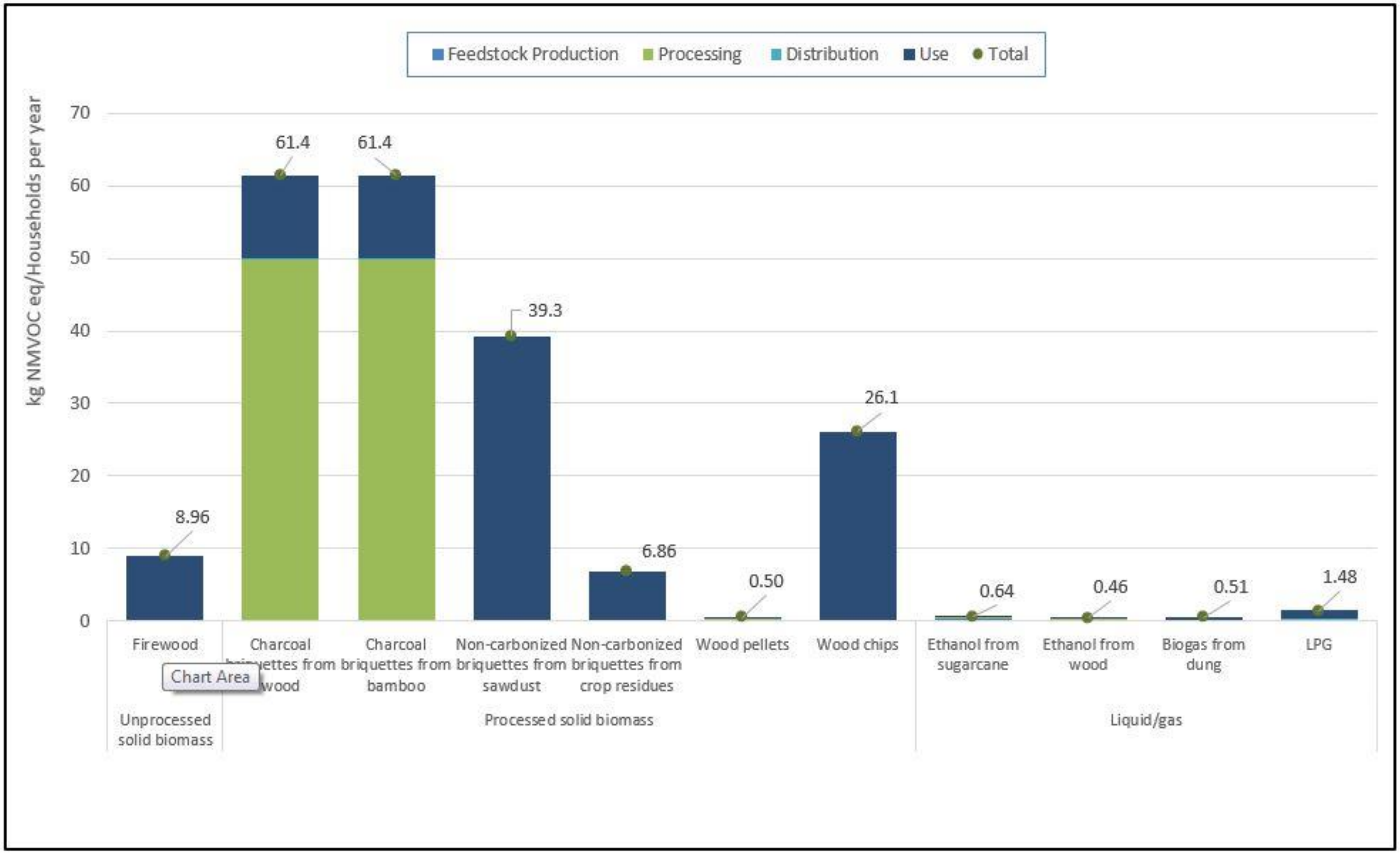


Figure A-35. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (Bangladesh)

To produce, distribute and use cooking fuels by a single household per year

A.4.3 Economic Indicators for Bangladesh

A.4.3.1 Fuel Use

The percentages of the population in Bangladesh using various fuel types as their primary cooking fuel are shown in Figure A-36. Biomass dominates cooking fuel use, with about 83 percent of the population using some form of biomass, and about 8 to 9 percent of the population uses LPG or dung.[175] The biomass used consists mostly of firewood and unprocessed crop residues, particularly rice husks, or any fuel that is free for collecting,[176] but there is also some use of bamboo.[177] Those in rural areas primarily use biomass fuels, while about 50 percent of urban residents use biomass and the remainder use LPG or other types of fuels.[178] There is some commercial production of rice husk briquettes for urban users (with 900 briquetting machines in the country),[179,180] as well as some production of wood pellets,[181] and there are about 50,000 household and village-level biogas digesters in rural areas. Ethanol use as a cooking fuel is almost non-existent, in spite of some past government initiatives to promote this fuel for cooking.[182,183]

During the monsoon season it can be difficult to gather fuels, so households must purchase more fuel. There is approximately a 5 percent increase in the number of people purchasing fuel in the wet season compared to the dry season. [184]

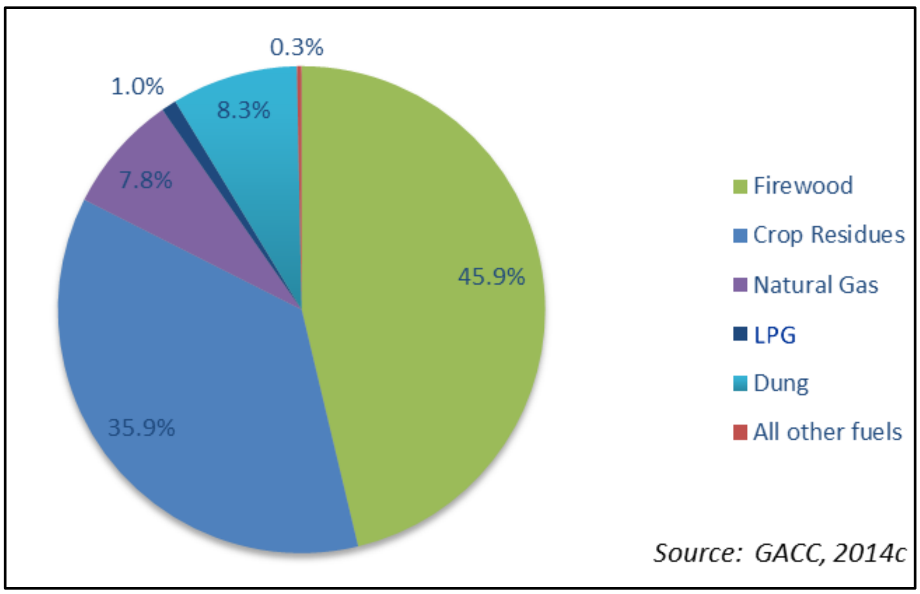


Figure A-36. Current Cooking Fuel Mix in Bangladesh

A.4.3.2 Fuel Imports, Exports, Production, and Demand in Bangladesh

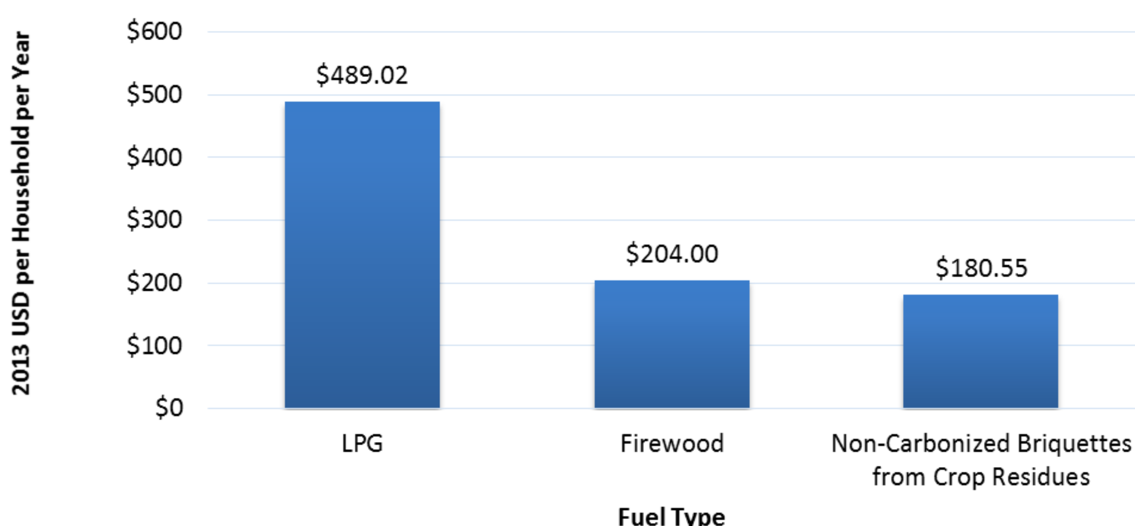
Table A-39 shows the levels of imports, exports, production, and demand (assumed to be equal to current consumption) of several fuels in Bangladesh. The data on total and household demand do not differentiate between fuel use for cooking and fuel use for other purposes such as heating. Bangladesh is unable to meet most of its LPG demand with domestic production, and so imports make up about 80 percent of demand.[185] Ethanol production is quite high and is about ten times higher than demand.[186] While no specific data are available on exports, most of this ethanol is likely exported. Bangladesh produces about 26.8 million tonnes of firewood,[187] but this figure is unlikely to capture firewood that is gathered by the end user for cooking fuel.

Table A-39. Fuel Imports, Exports, Production, and Demand in Bangladesh (Tonnes per Year)

Fuel	Imports	Exports	Production	Demand		Sources
				Total	Household	
LPG	32,000	No data	8,000	40,000	40,000	UNSD, 2011
Ethanol	No data	No data	208,839	19,400	No data	OECD/FAO, 2014
Firewood	No data	No data	26,815,639	No data	No data	FAO, 2014
Charcoal Briquettes	50	60	326,700	326,700	No data	UNSD, 2011

A.4.3.3 Fuel Cost in Bangladesh

Figure A-37 shows the price per household per year for the cooking fuels in Bangladesh for which data are available. LPG is the most expensive fuel, at about $490 per household per year. Firewood is often free for collecting in rural areas, but can cost $204 per household per year if purchased. Non-carbonized crop residue briquettes are the least expensive fuel, at $181 per household per year.



Note: No data available for fuel types not included.

Source: Accenture, 2012a

Figure A-37. Fuel Cost Indicator for Cooking Fuels in Bangladesh.

A.4.4 Social Indicators for Bangladesh

A.4.4.1 Government Policies/Programs

Given the relative novelty of the feedstock-fuel combinations in the present study, limited information is available from Bangladesh's government regarding the promotion of or resistance to specific cookfuels. Evidence from one assessment suggests the government tries to regulate the LPG market; however, despite a cut in government duties, LPG costs increased approximately 30 percent from 2011 to 2012.[188] Relatedly, if LPG is too expensive in urban areas, the government supplies users with natural gas instead.[189] Similar to the limited efficacy of government policies regarding LPG, ethanol is used minimally as a cooking fuel despite past government initiatives to promote its adoption.[190]

Despite these challenges, progress is observed as evidenced by government microfinance programs (through Grameen Bank and other institutions) that support clean cookstove adoption and entrepreneurism.[191] The government-owned Infrastructure Development Company, Ltd., which has installed over 1.2 million solar home systems, and public-private partnerships, such as those developed through the government's Sustainable Energy for Development (SED) Program, which has helped construct over 1,500 commercial biogas plants,[192] have also gained traction. Although these initiatives are aimed at improving rural electrification and have not necessarily led to improved access to clean cooking methods (for example, the solar home systems mentioned above are primarily used for lighting and charging mobile devices),[193] they illustrate the potential for the uptake of non-traditional energy sources in Bangladesh.

With respect to the energy sector as a whole, the Bangladeshi government recently identified three priorities:

1. Address the inadequate supply of electricity relative to demand,
2. Reduce dependency on single energy source (gas) for electricity generation, and
3. Promote the use of renewable energy.

To these ends, the government has increased the price of electricity sold through the state-run power company as well as promoted a variety of sustainable energy initiatives.[194] Key programs (some of which began prior to the codification of the tenets above) include the Ministry of Power's 2008 Renewably Energy Policy (created the Sustainable and Renewable Energy Development Agency (SREDA), which coordinates tax exemptions for the renewable energy sector, sets policy targets, and more[195]), the Ministry of Environment and Forest's development of a Climate Change Strategy and Action Plan, and the national government's push to improve energy affordability by providing fuel subsidies for all (presumably fossil) fuels except coal.[196]

While not cookfuel-, cookstove-, or energy sector-specific, the National Policy for the Advancement of Women "aims to promote and protect women's rights across a number of areas such as health, employment, and poverty reduction,"[197] and has the potential to facilitate female engagement in the clean cooking sector.

A.4.4.2 Supply & Access Challenges

The availability of firewood is diminishing due to a deforestation rate of 0.2 percent per year.[198,199] Although deforestation has largely been reversed through concentrated action by the government and its development partners,[200] the 12.1 million rural households (36 percent of the total population) who rely on collected fuels[201] continue to face energy security issues. Moreover, firewood acquisition patterns are changing among those with the ability to pay for some or all of their cooking energy: from 2004 to 2011 the number of rural households purchasing firewood increased from 40 percent to approximately 65 percent, with some variation based on the season. The 2.9 million urban households who rely on a mix of firewood, kerosene, and electricity to cook[202] might also be impacted by Bangladesh's shifting forestry sector.

Other fuels cannot be acquired reliably due to poor or diverted feedstock supplies. For example, little cellulose or sawdust is available for ethanol cookfuel production[203] since most of these feedstocks appear to support the production of biofuel for transportation. Although the competition for ethanol feedstocks is not noted explicitly in the literature, Bangladesh's ethanol production is documented at ten times its consumption,[204] and with no substantial use of ethanol for cooking,[205] a possible conclusion is the diversion of ethanol production away from cookfuel towards the more lucrative biofuel.

Similarly, although bamboo is available, a lack of briquetting infrastructure means it is typically only burned raw.[206] LPG is unique in that strong infrastructure is in place in Bangladesh's large urban centers, but historically high prices have reduced demand to the point that only about 8 percent of the population is using the fuel[207] and it is not widely available.[208]

A.4.4.3 Distribution & Adoption Challenges

In addition to cost barriers, one of the key challenges to the adoption of alternative fuels in Bangladesh relates to a lack of awareness regarding the environmental, social, and health impacts of household fuel choices. Although awareness is only possible after supply is available and affordable, limited outreach efforts have been aimed at promoting (or marketing) the benefits of alternative fuels.[209,210] Certain infrastructural barriers exist, as well. With 72 percent of the population living in rural areas and only 30 percent of the roads paved,[211] enterprises looking to scale up transportation-sensitive fuel industries such as LPG could have substantial difficulties.

A challenge specific to women is that they tend not to have the necessary collateral to apply for loans to afford the upfront cost of alternative cooking solutions (such as biogas digesters) or even have the financial positioning required to afford an improved biomass stove.[212] If women struggle to find financing options for the procurement of nontraditional cooking options for their homes, it indicates the substantial barriers they would face when trying to borrow at the enterprise level.

A.4.4.4 Protection & Safety

Collection of animal dung and crop residues usually occurs somewhat close to the household, and no safety issues were found in the literature. Firewood collection by women and young girls in remote locations, however, creates opportunities for physical and sexual harassment. Following from and augmenting these direct risks, women and young girls who survive acts of physical and sexual violence can be perceived as having humiliated their families and may face domestic violence at home and societal abuse in their communities.[213]

Other threats to long-term health from travelling long distances and repeatedly bending to manually gather fuels include spinal column damage, sprains, and strains.[214] Moreover, these repetitive stress injuries can affect the performance of other obligations.

A.4.4.5 Time & Drudgery

Women in Bangladesh are the primary collectors of biomass residues,[215] spending approximately 36 person-days per year on preparing biomass for cookfuel.[216] With increasing deforestation—only about 11 percent of Bangladesh is under forest cover[217]—and longer distances to travel to make up for biomass shortages, it is reasonable to expect that the fuel collection time and labor demanded of rural women will increase.[218] Although a fuel-specific and gender-disaggregated breakdown of the time spent collecting fuel is not possible, some data are available. For example, rural households in Bangladesh spent on average 58.9 hours annually collecting firewood, 116.4 hours annually collecting tree leaves and crop residues, and 24.72 hours annually collecting animal dung.[219] Illustrating the potential for nontraditional fuels to positively impact these fuel collection times is evidence from one study that found substantial time savings when those relying on manually collected firewood switched to rice husk briquettes.[220]

Potential time savings also exist with respect to cooking. Bangladeshi women have primary responsibility for cooking in both urban and rural settings, spending an average of four to five hours per day cooking over traditional fuels and six to eight hours per day in the kitchen total. A substantial driver of these cooking times is lunch, which typically takes three to five hours to prepare.[221] Although fuel-specific cooking times for alternative fuels are not available in Bangladesh, evidence from countries with similar traditional fuel landscapes, such as India, suggests there are opportunities for time savings with the adoption of liquid and gaseous fuels.[222]

A.4.4.6 Income Earning Opportunities

Given the newness of the feedstock-fuel combinations in the present study, limited information regarding the income earning opportunities associated with specific cookfuels is available. There is anecdotal evidence of enterprises who produce pellets from wood experiencing success by marketing their product as low cost relative to other alternative fuels and relatively smoke-free compared to firewood. Similar opportunities are thought to be available for producers of charcoal briquettes from wood, especially as organizations continue to raise awareness about social issues such as health impacts to women who cook over traditional fuels and environmental issues such as deforestation.[223]

Another opportunity market is present in the biogas sector. Grameen Shakti—formed initially to produce photovoltaic solar-home systems[224]—has installed over 30,000 biogas plants in Bangladesh since 2005, thanks in part to its innovative microfinance solutions that help buyers overcome the upfront costs of new biogas systems.[225,226] Grameen Shakti has been able to create jobs for their employees who supervise and service the plants as well as the local masons and laborers who install them.[227] Moreover, income earning opportunities are present for end users who can sell the biogas or bio-fertilizer (slurry) they produce to their neighbors.[228]

A.4.4.7 Opportunities for Women Along the Value Chain

According to the Global Alliance for Clean Cookstoves 2013 Results Report, the clean cookstove industry in Bangladesh currently has 670 employees (24 percent of whom are women) and 13,422 microentrepreneurs (63 percent of whom are women).[229] However, there are currently no data available to estimate potential increases of skills for women with respect to specific fuels. Formal networks for women interested in the energy sector are relatively new in Bangladesh and involvement, as of 2004, was viewed more as a leisure activity than an opportunity for professional development.[230]

Additionally, general insights suggest that there are substantial societal barriers facing Bangladeshi women who want to become involved in the cookfuel sector.[231] This trend is supported by a 2005 study—though not fuel- or energy-sector specific—that found all rural microenterprises included in the survey were owned by men, and that women represented only 1.5 percent of all surveyed employees. The authors go on to note that a 2003 survey with a similar scope found that women represented 9 percent of the rural labor force.[232] A key reason for the gender divide in rural Bangladesh's workforce is that a large share of many women's time is consumed with household responsibilities. Moreover, religion and custom limit women's access to markets and other areas of commercial activity. As such, women-headed enterprises tend to be located in the home and operate as cottage industries. Women operating in these informal sectors have less access to technical training, financial resources, and new technologies. In aggregate, these barriers provide limited incentives for involvement in the cooking fuel sector.[233] On the other hand, if attitudes towards women in the public sphere become more progressive, there are no structural reasons why women's involvement in fuel manufacture and distribution could not expand.[234]

Latin America

A.5 Detailed Results for Guatemala

A.5.1 Overview of Guatemala

Guatemala is Central America's most populous country,[235] with the population almost equally divided between urban and rural areas.[236] Overall, the dominant cooking fuels currently used in Guatemala are unprocessed solid fuels (e.g., firewood and crop residues) and LPG. Adequate fuel supply is a key consideration. For example, Guatemala has shown an overall trend of an approximately 1.5 percent decrease in forest land per year over recent years,[237] and 48 percent of Guatemala's land area is under the threat of severe drought.[238]

Fuel cost is another key issue. Fifty-four percent of the population is under the national poverty line of about $3.21 per capita per day,[239] and approximately 14 percent of the Guatemalan population lives below the international poverty line ($1.25 per capita per day).[240] Due to the poverty in Guatemala, many households can only afford to purchase fuel a day at a time.[241] Even those who can afford cleaner cooking fuels may still use biomass fuels to some extent. For example, a staple in the Guatemalan diet is beans, which require long cooking times and therefore may be too expensive to cook using a cleaner purchased fuel such as LPG.

The following sub-sections address the environmental, economic, and social considerations related to cooking fuels and stoves for Guatemala in greater detail.

A.5.2 Environmental Indicators for Guatemala

This section covers the detailed Guatemala LCA results for the ten environmental indicators assessed for each fuel. The stove thermal efficiency by fuel and the fuel heating values employed in this study to calculate the LCA results are provided in Table A-40 and Table A-41, respectively. The remainder of this section presents results for each environmental indicator.

Table A-40. Stove Thermal Efficiency Applied by Fuel for Guatemala

Fuel Type	Stove Thermal Efficiency	Sources
Firewood	15.0%	GACC, 2010
Charcoal Briquettes from Wood	28.7%	Pennise et al., 2001
Charcoal Briquettes from Bamboo	28.7%	Pennise et al., 2001
Non-Carbonized Briquettes from Sawdust	20.0%	Urban Uganda, 2015
Non-Carbonized Briquettes from Crop Residues	31.0%	GACC, 2015a
Wood Pellets	53.0%	Jetter et al., 2012
Wood Chips	31.0%	GACC, 2015a
Ethanol from Sugarcane	53.0%	Aprovecho Research Center, 2009
Ethanol from Wood	53.0%	Aprovecho Research Center, 2009
Biogas from Dung	55.0%	Singh et al., 2014
LPG	57.0%	Singh et al., 2014

Table A-41. Fuel Heating Values for Guatemala

Fuel Type	HHV (MJ/kg)	Sources
Firewood	17.4	Boy et al., 2000
Charcoal Briquettes from Wood	29.2	Pennise et al., 2001
Charcoal Briquettes from Bamboo	18.6	Pennise et al., 2001
Non-Carbonized Briquettes from Sawdust	18.6	Kaur et al., 2012 Grover et al., 1996 Davies et al., 2013 Vyas et al., 2015
Non-Carbonized Briquettes from Crop Residues	16.08	Zhang, et al. 2000
Wood Pellets	17.94	Jetter et al., 2012
Wood Chips	17.4	Boy et al., 2000
Ethanol from Sugarcane	28.3	Aprovecho Research Center, 2009
Ethanol from Wood	28.3	Aprovecho Research Center, 2009
Biogas from Dung	18.2	Singh et al., 2014
LPG	53.4	Singh et al., 2014

A.5.2.1 Total Energy Demand

Table A-42 and Figure A-38 display the total energy demand impact results for fuels in Guatemala by life cycle stage. Total energy demand sources consist of non-renewable fuels (natural gas, petroleum, coal, and nuclear) and "renewable" fuels (e.g. biomass, hydro). Energy demand tracks all energy inputs across the life cycle of the fuel, with energy impacts shown at the point of use of the relevant fuel.

The total energy demand results are largely a function of the fuel heating value and thermal efficiency of the fuel and stove combination (Table A-40 and Table A-41). Stoves with higher efficiencies (e.g., LPG, biogas, ethanol, and wood pellets) have a lower total energy demand overall, because more of the heating value of the fuel is converted into useful cooking energy and therefore less fuel must be produced, transported, and burned to deliver the same amount of cooking energy.

A number of observations can be made regarding energy results for the various types of fuels. For sugarcane ethanol, the feedstock energy results include not only the energy value of the sugar that is converted to ethanol but also the energy content of the bagasse, which provides the majority of energy used to process the sugarcane to ethanol. In Guatemala, it is assumed the sugarcane is converted directly to ethanol, similar to the supply-chain seen in Brazil. A co-benefit of ethanol production is the production of electricity, which may be exported. As discussed in the Appendix B methodology, this model employs the cut-off allocation methodology; therefore, a credit is not given here to the sugarcane or wood ethanol for exported electricity, so the energy demand impacts for ethanol should be considered as the upper bounds for these fuel types.

For wood fuels, the wood pellets and wood chips have a lower total energy demand than traditional firewood. Wood chips and wood pellets typically have a lower moisture content, greater energy content, and greater surface area than the traditional solid biomass, which allows the fuel to combust more efficiently. It is also more common to see improved cookstoves, which have higher stove thermal efficiencies, used in combination with the wood chips and wood pellets in Guatemala.

For briquettes, the energy demand impact for the carbonized briquettes from wood and bamboo is the greatest compared to other fuels due to the lower stove efficiencies for charcoal stoves in Guatemala and the charcoal kiln energy impacts. That is, additional energy is consumed when burning firewood at the kiln to produce charcoal prior to charcoal briquette utilization in a cookstove. It is assumed the charcoal from wood and bamboo in Guatemala is produced in a surface kiln.[242] All non-carbonized sawdust briquettes in Guatemala are modeled as pressed manually and dried naturally to 10% moisture content. This requires 1.5 kg wood input to each 1 kg briquette, assuming a 40% moisture content of the original greenwood.[173]

Overall, liquid and gas fuels as well as processed solid biomass fuels not requiring additional combustion of solid fuel for processing (e.g., wood pellets) lead to the lowest overall total energy demand impacts.

Table A-42. Total Energy Demand (MJ) for Cooking Fuel Types (Guatemala)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed solid biomass	Firewood	0	0	0	104,300	104,300
Processed solid biomass	Charcoal briquettes from wood	0	156,605	0.11	54,483	211,088
	Charcoal briquettes from bamboo	0	153,202	0.11	54,483	207,685
	Non-carbonized briquettes from sawdust	0	39,227	2.51	78,183	117,412
	Non-carbonized briquettes from crop residues	0	1,920	0.019	50,441	52,361
	Wood pellets	0	10,695	1.49	29,503	40,199
	Wood chips	0	601	0.034	50,441	51,041
Liquid/gas	Ethanol from sugarcane	1,282	11,480	456	29,503	42,721
	Ethanol from wood	0	3,626	0.43	29,503	33,129
	Biogas from dung	0	0	0	28,453	28,453
	LPG	486	20,343	368	27,433	48,630

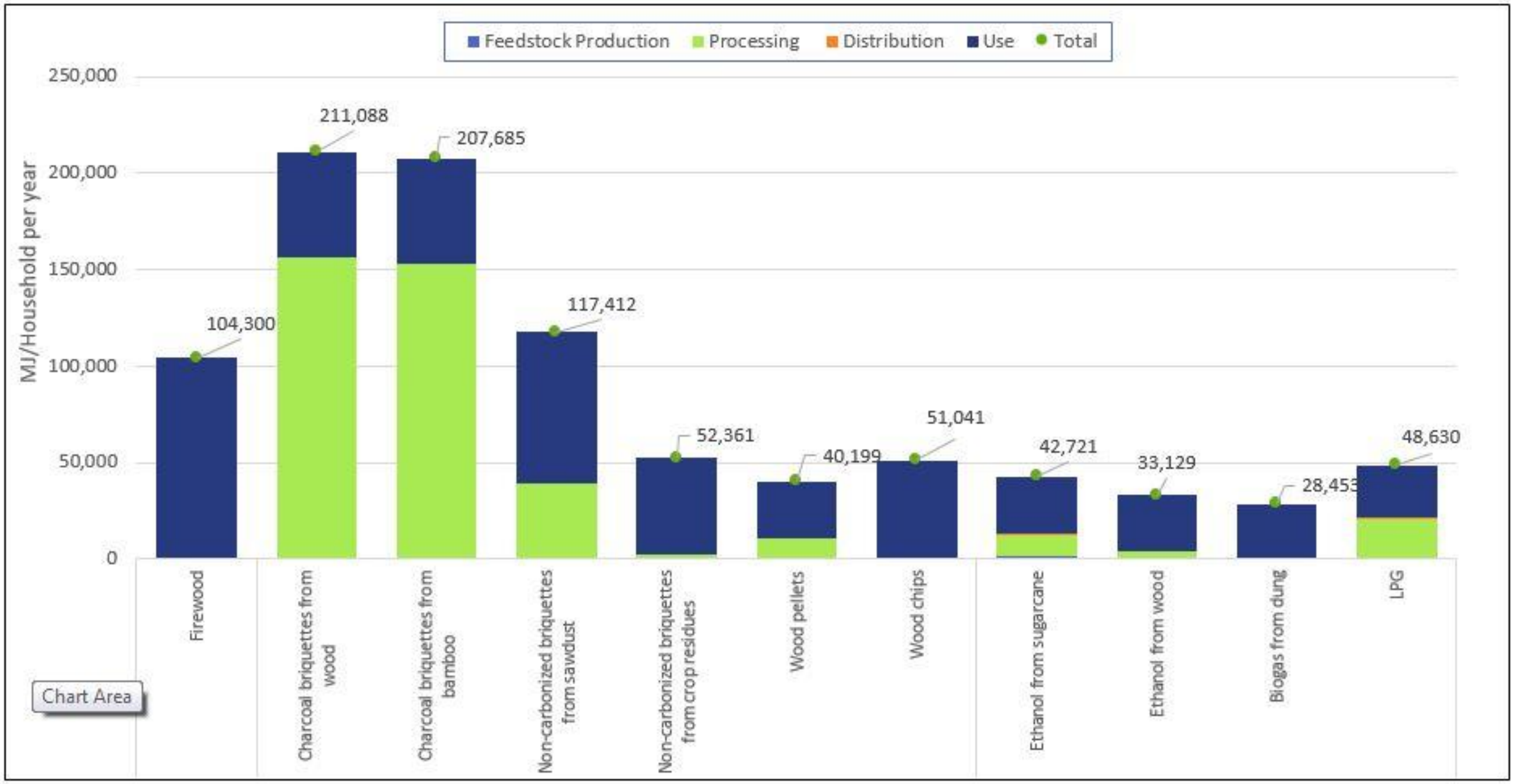


Figure A-38. Total Energy Demand (MJ) for Cooking Fuel Types (Guatemala)
To produce, distribute and use cooking fuels by a single household per year

A.5.2.2 Net Energy Demand

Table A-43 and Figure A-39 illustrate the net energy demand impact results for fuels in Guatemala by life cycle stage. Net energy demand is calculated in the same way as total energy demand, with the final energy delivered to the cooking pot deducted from the results. The net energy indicator is, therefore, the additional energy required for the life cycle of the cookstove fuel beyond what is delivered to the consumer for cooking purposes. For Guatemala, 42.8 MJ of cooking energy are consumed per household per day, which equates to 15,637 MJ per household per year.[243] Utilization of unprocessed solid biomass (i.e. firewood) consumes a little less than seven times more energy than is provided to the pot, as listed in the last column of Table A-43. Similar levels of net energy demand are seen for non-carbonized briquettes from sawdust. The highest net energy demand impacts are from charcoal briquettes due to the level of wood required to provide energy for the surface kiln in Guatemala. The lowest overall net energy demand is calculated for non-carbonized briquettes from crop residues, wood pellets, wood chips, ethanol from wood, biogas from dung, and LPG. Production, processing, distribution, and use of these less energy intensive fuels uses 0.82 to 2.35 times the amount of energy delivered to the pot.

Table A-43. Net Energy Demand (MJ) for Cooking Fuel Types (Guatemala)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total	Net Energy Consumed: Delivered Energy
		Feedstock Production	Processing	Distribution	Use		
Unprocessed solid biomass	Firewood	0	0	0	88,663	88,663	5.67
Processed solid biomass	Charcoal briquettes from wood	0	156,605	0.11	38,846	195,451	12.5
	Charcoal briquettes from bamboo	0	153,202	0.11	38,846	192,049	12.3
	Non-carbonized briquettes from sawdust	0	39,227	2.51	62,546	101,776	6.51
	Non-carbonized briquettes from crop residues	0	1,920	0.019	34,804	36,724	2.35
	Wood pellets	0	10,695	1.49	13,866	24,563	1.57
	Wood chips	0	601	0.034	34,804	35,405	2.26
Liquid/gas	Ethanol from sugarcane	1,282	11,480	456	13,866	27,084	1.73
	Ethanol from wood	0	3,626	0.43	13,866	17,492	1.12
	Biogas from dung	0	0	0	12,817	12,817	0.82
	LPG	486	20,343	368	11,796	32,993	2.11

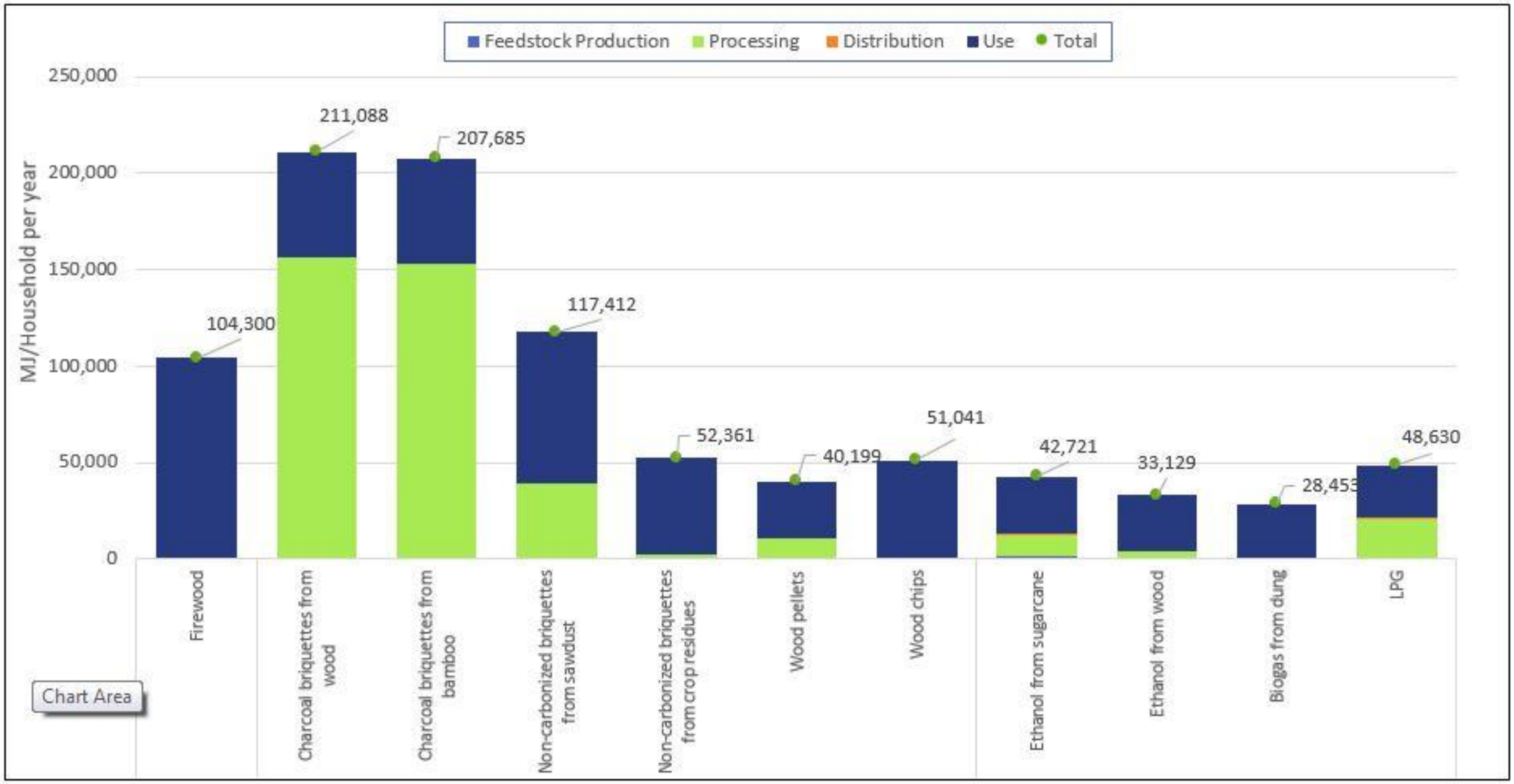


Figure A-39. Net Energy Demand (MJ) for Cooking Fuel Types (Guatemala)

To produce, distribute and use cooking fuels by a single household per year

A.5.2.3 Global Climate Change Potential (100a)

Table A-44 and Figure A-40 present the global climate change potential (GCCP) impact results for fuels in Guatemala by life cycle stage. The GCCP impact category represents the heat trapping capacity of greenhouse gases over a 100 year time horizon. Fossil fuel GCCP impacts are dominated by combustion emissions in the cookstove use stage.

Biogas GCCP impacts are primarily from methane leakage during the production of biogas in an anaerobic digester. Sugarcane ethanol, charcoal briquettes from bamboo, and briquettes from crop residues are derived from renewable biomass that removed CO_2 from the atmosphere during growth; therefore, the CO_2 emissions released from combustion of these fuels is considered carbon neutral, as discussed in detail in the Appendix B methodology. Impacts for these renewable fuels during the use phase are driven by nitrous oxide and methane emissions during cookstove use. Impacts associated with fertilizer production and emissions from application also play a role in the sugarcane ethanol overall impacts.

Based on the decreasing trend in forest area in Guatemala, all of the wood harvested for use as cooking fuel is considered unsustainably sourced, and the combustion emissions for the non-sustainable use of wood are not considered carbon-neutral. This adjustment is also applied to other wood fuels (wood-derived charcoal briquettes, wood pellets and wood chips), but not to fuels derived from wood wastes (wood ethanol and non-carbonized briquettes from sawdust). With the cut-off modeling methodology used in this analysis, wood wastes are treated as a “free” product (all burdens are allocated to the primary wood product, e.g., lumber, which is outside the scope of this study), so emissions of biomass CO_2 for fuels derived from wood waste are treated as carbon neutral. For charcoal briquettes, GCCP impacts for carbonization of the wood in the kiln are comparable in magnitude to the emissions from combustion of the charcoal briquettes in a cookstove. Charcoal kiln impacts are largely driven by the methane emissions during the carbonization process. Combustion emissions for bamboo-derived charcoal briquettes are lower than for wood-derived charcoal briquettes because bamboo is a renewable crop and all combustion emissions are considered carbon-neutral, while none of the wood combustion emissions are considered carbon-neutral, since the wood supply in Guatemala is considered non-renewable based on the decreasing forest area. All GHGs associated with the production and combustion of LPG, including CO_2 emissions from cooking, are considered fossil-derived and accounted for in the GCCP impacts.

Table A-44. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (Guatemala)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	11,728	11,728
Processed Solid Biomass	Charcoal Briquettes from Wood	0	10,217	186	9,280	19,682
	Charcoal Briquettes from Bamboo	0	4,712	186	718	5,616
	Non-Carbonized Briquettes from Sawdust	0	0	186	1,194	1,380
	Non-Carbonized Briquettes from Crop Residues	0	0	1.44	347	349
	Wood Pellets	0	250	110	5,360	5,720
	Wood Chips	0	42.5	2.51	5,669	5,714
Liquid/Gas	Ethanol from Sugarcane	179	10.1	32.6	14.9	236
	Ethanol from Wood	0	76.8	31.5	14.9	123
	Biogas from Dung	0	144	0	20.7	164
	LPG	271	189	23.1	4,285	4,768

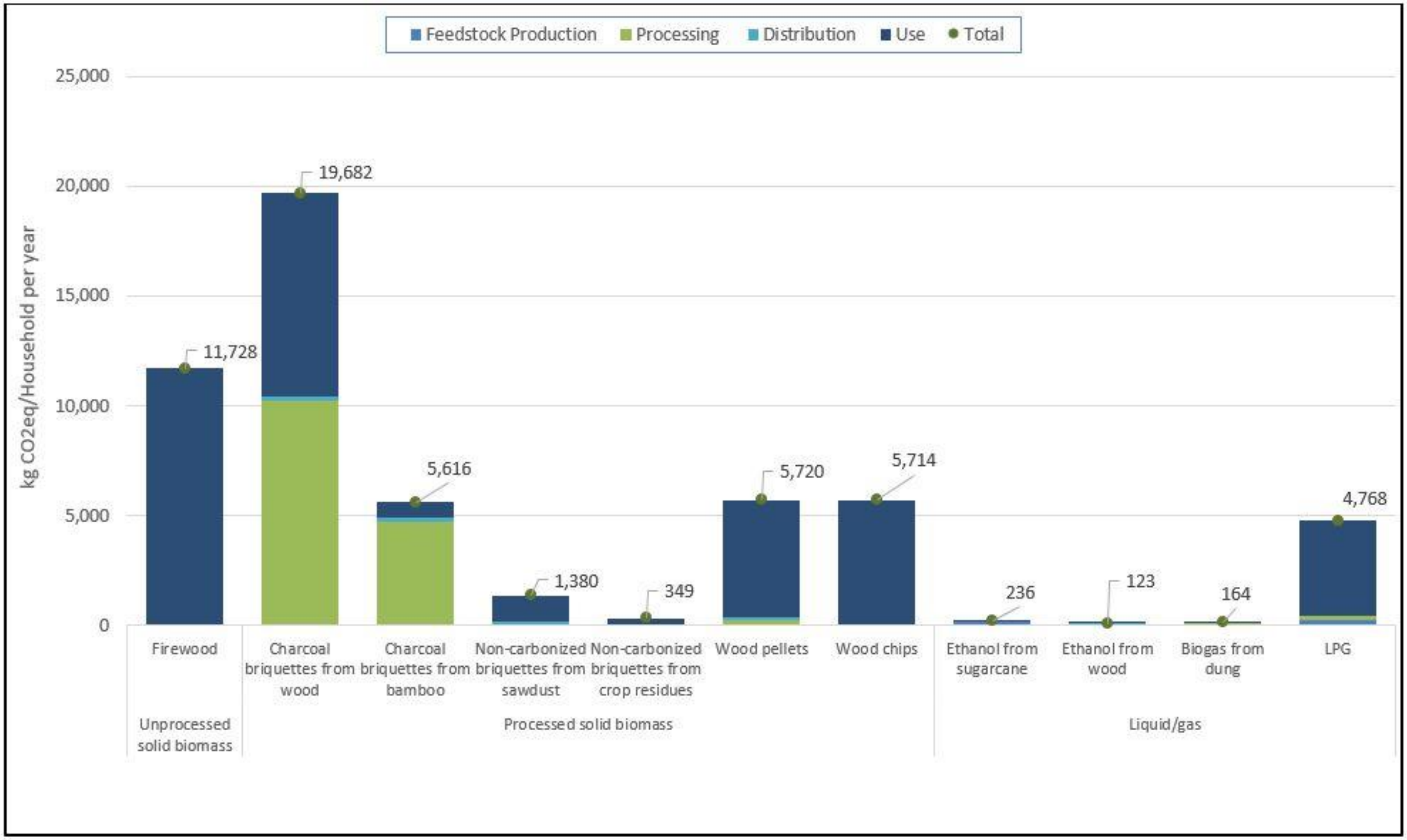


Figure A-40. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (Guatemala)
To produce, distribute and use cooking fuels by a single household per year

A.5.2.4 Black Carbon and Short-Lived Climate Pollutants

Table A-45 and Figure A-41 display the black carbon and short-lived climate pollutants impact results for fuels in Guatemala by life cycle stage. Black carbon (BC) is formed by incomplete combustion of fossil and bio-based fuels. BC is the carbon component of particulate matter (PM) with aerodynamic diameter less than or equal to 2.5 microns (PM2.5). This is the size of PM that most strongly absorbs light and thus has potential radiative forcing effects (i.e., potential to contribute to global warming). Potential climate forcing impacts resulting from BC emissions include direct, albedo (i.e., fraction of solar energy hitting the earth that is reflected), and other effects. BC is emitted with other particles (e.g. organic carbon) and criteria pollutants such as nitrogen and sulfur dioxides. Though some of these co-pollutants may exert a cooling effect on climate, the net effects of BC emissions likely contribute to global climate warming. Appendix B shows the 20 year global warming potential and black carbon equivalent values used in the results calculation. Results are presented here based on BC equivalents. The highest BC impacts are seen for charcoal briquettes followed by firewood, which tend to have high particulate matter emissions when combusted. Similarly, high emissions of particulate matter are seen in the Guatemalan charcoal surface kiln, which combusts wood to carbonize the fuel. Utilization of the liquid and gas fuels result in the lowest overall BC impacts. Some life cycle stages have negative BC equivalent impacts, which is the case when emissions of SO_x and organic carbon (pollutants with net cooling effects on the climate), are greater than the emissions of BC and other co-emitted pollutants that lead to short term warming impacts.

Table A-45. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (Guatemala)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	9.97	9.97
Processed Solid Biomass	Charcoal Briquettes from Wood	0	64.1	0.012	4.00	68.1
	Charcoal Briquettes from Bamboo	0	64.1	0.012	4.00	68.1
	Non-Carbonized Briquettes from Sawdust	0	0	0.012	7.48	7.49
	Non-Carbonized Briquettes from Crop Residues	0	0	9.7E-05	2.30	2.30
	Wood Pellets	0	-0.0047	0.0074	0.33	0.33
	Wood Chips	0	0.010	6.9E-04	4.83	4.84
Liquid/Gas	Ethanol from Sugarcane	0.0011	-0.0044	-0.018	0.044	0.023
	Ethanol from Wood	0	0.026	0.0021	0.044	0.072
	Biogas from Dung	0	0	0	0.11	0.11
	LPG	-0.093	-0.38	-0.0082	0.086	-0.40

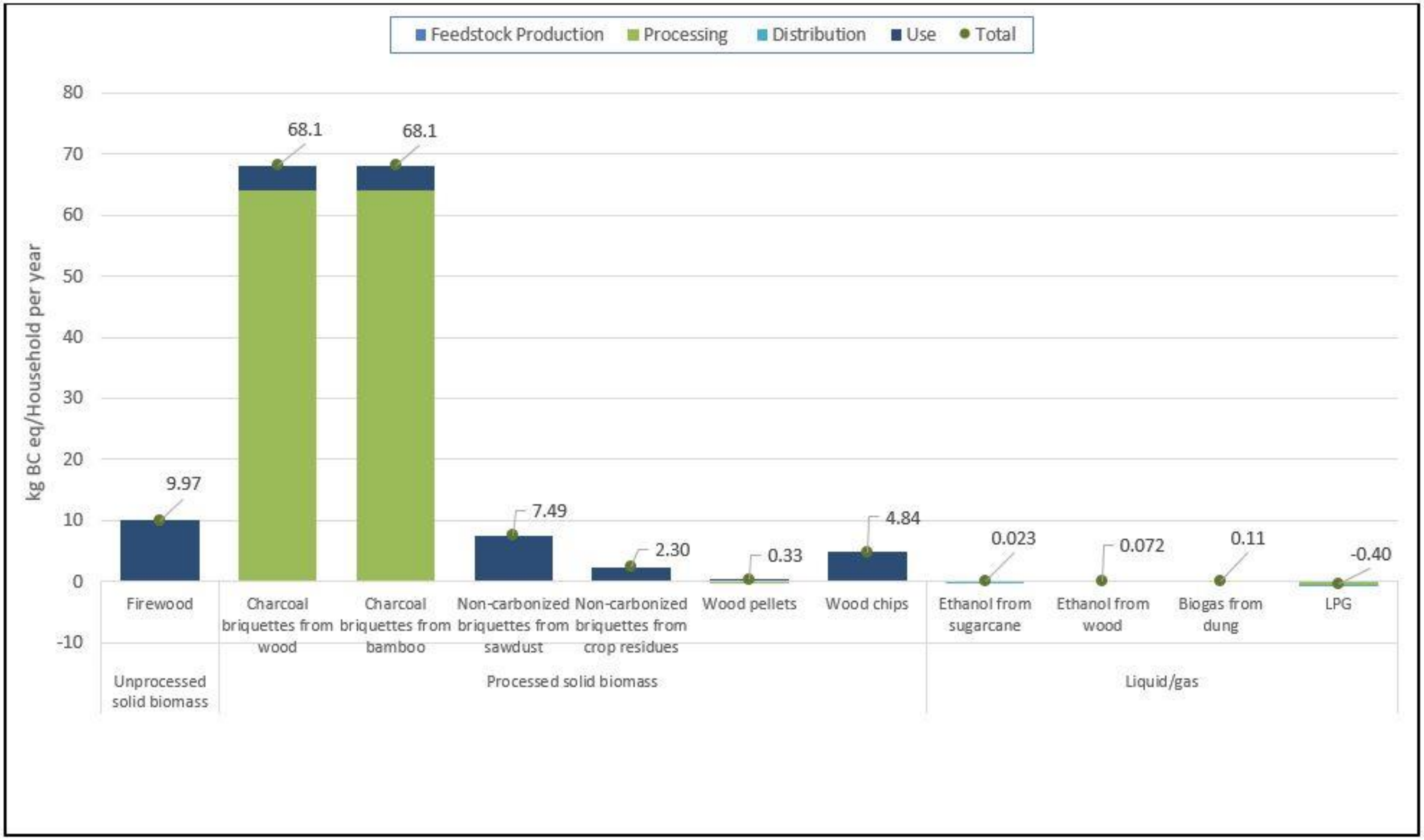


Figure A-41. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (Guatemala)
To produce, distribute and use cooking fuels by a single household per year

A.5.2.5 Particulate Matter Formation Potential

Table A-46 and Figure A-42 show the particulate matter formation impact results for fuels in Guatemala by life cycle stage. Particulate matter can contribute to many negative health impacts such as effects on breathing and respiratory systems, damage to lung tissue, cancer, and premature death. Primary and secondary pollutants leading to particulate matter formation as well as PM2.5 are characterized here to kg PM10 eq. Charcoal briquette fuels lead to the greatest particulate matter formation impacts. For charcoal briquettes, the carbonization of the wood in the kiln dominates the overall particulate matter life cycle impacts. The next most impactful fuels are firewood and non-carbonized briquettes from sawdust. Advanced liquid fuels as well as biogas and wood pellets have comparably small particulate matter impacts.

Table A-46. Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (Guatemala)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	**Processing**	**Distribution**	**Use**	**Total**
Unprocessed Solid Biomass	Firewood	0	0	0	34.0	34.0
Processed Solid Biomass	Charcoal Briquettes from Wood	0	293	0.32	10.9	305
	Charcoal Briquettes from Bamboo	0	293	0.32	10.9	305
	Non-Carbonized Briquettes from Sawdust	0	0	0.32	25.5	25.8
	Non-Carbonized Briquettes from Crop Residues	0	0	0.0025	9.51	9.51
	Wood Pellets	0	0.68	0.19	1.61	2.49
	Wood Chips	0	0.16	0.0044	16.5	16.6
Liquid/Gas	Ethanol from Sugarcane	0.49	0.025	0.24	0.0067	0.76
	Ethanol from Wood	0	0.95	0.054	0.0067	1.01
	Biogas from Dung	0	0	0	1.21	1.21
	LPG	0.090	0.32	0.13	0.93	1.47

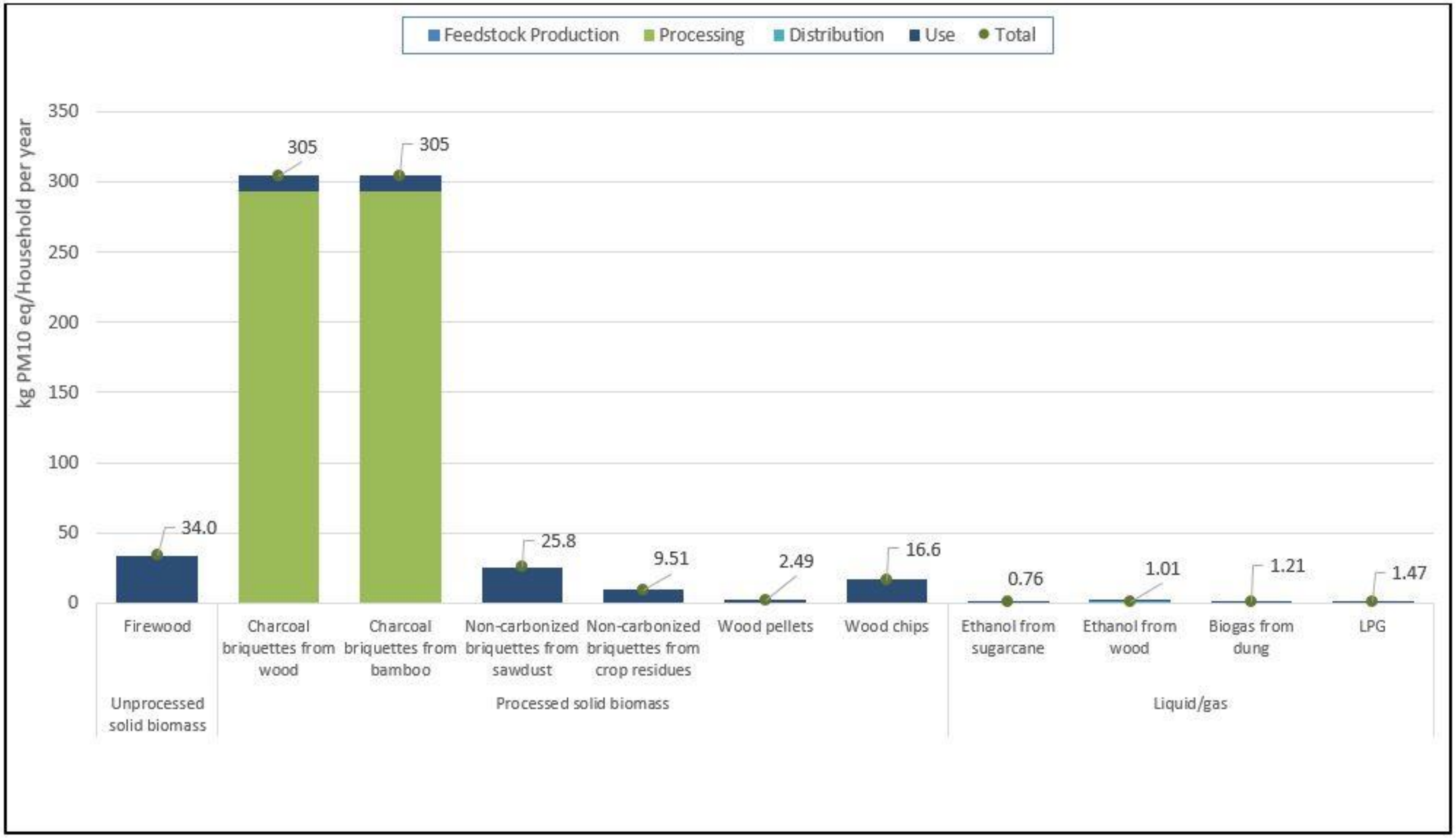


Figure A-42. Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (Guatemala)
To produce, distribute and use cooking fuels by a single household per year

A.5.2.6 Fossil Fuel Depletion

Table A-47 and Figure A-43 provide the fossil fuel depletion impact results for fuels in Guatemala by life cycle stage. Fossil depletion captures the consumption of fossil fuels, primarily coal, natural gas, and crude oil. All fuels are normalized to kg oil eq based on the heating value of the fossil fuel relative to the heating value of a kg of oil. The fossil depletion associated with firewood as well as biogas and ethanol from wood is negligible, as these fuels are not derived from fossil fuel, and collection of these fuels is done manually. While biomass fuels are not derived from fossil fuels, some fossil fuels may be consumed across the life cycle of these fuels for energy inputs to fuel production and processing, distribution, and disposal. Fossil depletion for wood pellets is associated with electricity usage for pelletization and some transport, while sugarcane ethanol fossil depletion is primarily from fertilizers during cane production, as well as diesel for farm operation and distribution of the feedstock and fuel. Some fossil depletion impacts are also seen for processing the wood chips (as discussed in detail in Appendix B, 100% of wood chipping is modeled as mechanized in Guatemala). Fossil depletion impacts are highest for LPG as this source of energy relies on fossil fuels.

Table A-47. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (Guatemala)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	**Processing**	**Distribution**	**Use**	**Total**
Unprocessed solid biomass	Firewood	0	0	0	0.079	0.079
Processed solid biomass	Charcoal briquettes from wood	0	0	0.060	0.096	0.16
	Charcoal briquettes from bamboo	0	0	0.060	0.24	0.30
	Non-carbonized briquettes from sawdust	0	0	0.060	0.055	0.12
	Non-carbonized briquettes from crop residues	0	0	4.7E-04	0.0090	0.0094
	Wood pellets	0	59.7	0.036	0.0028	59.8
	Wood chips	0	12.7	8.1E-04	0.038	12.7
Liquid/gas	Ethanol from sugarcane	29.6	1.22	10.8	0	41.6
	Ethanol from wood	0	16.7	0.010	0	16.7
	Biogas from dung	0	0	0	0	0
	LPG	16.7	697	12.6	940	1,667

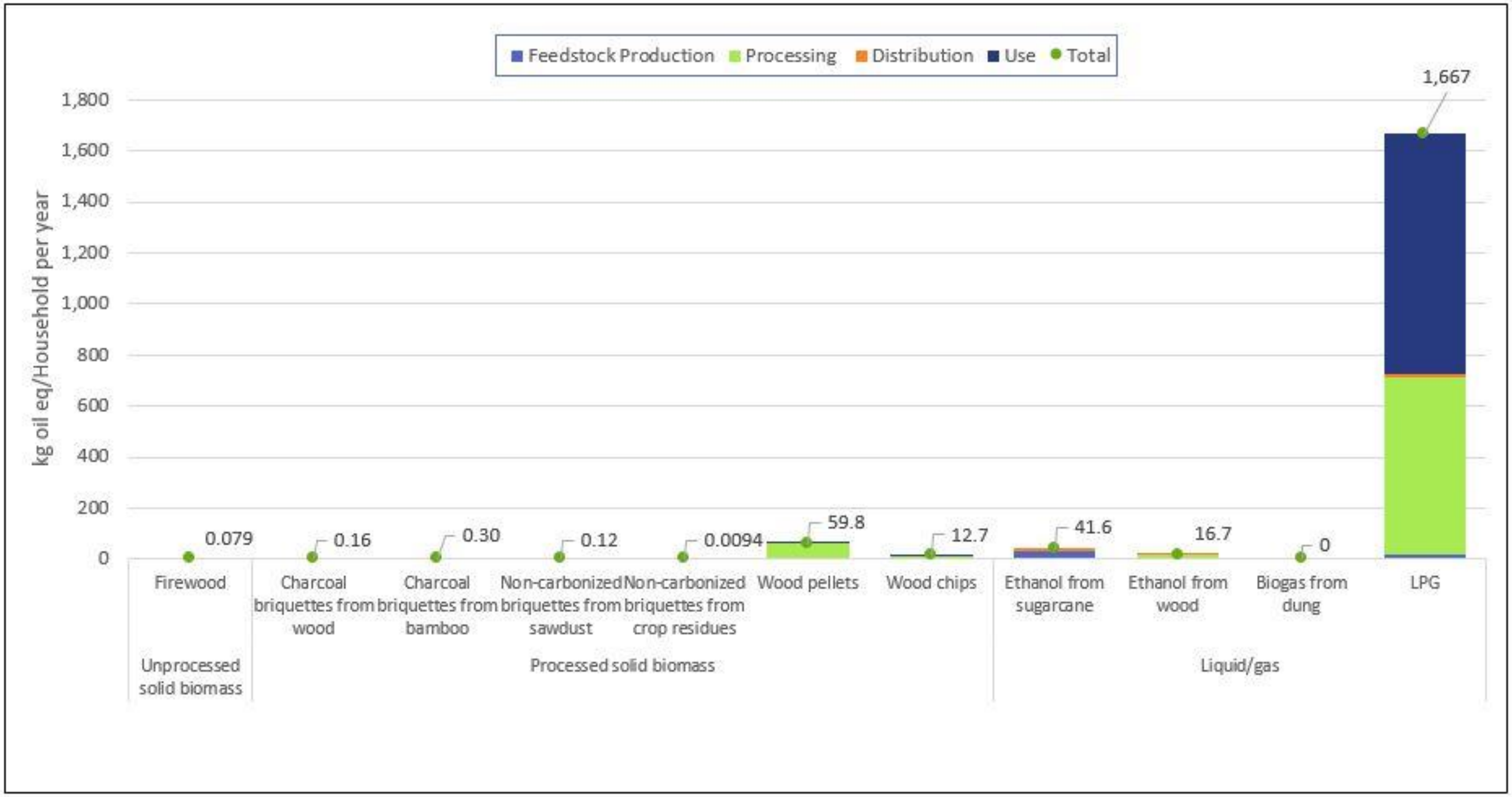


Figure A-43. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (Guatemala)
To produce, distribute and use cooking fuels by a single household per year

A.5.2.7 Water Depletion

Table A-48 and Figure A-44 illustrate the water depletion impact results for fuels in Guatemala by life cycle stage. Water depletion results are based on the volume of fresh water inputs over the life cycle of the assessed fuels. Water may be incorporated in the fuel product, evaporated, or returned to the same or different water body or to land. If the water is returned to the same water body, it is assumed the water is returned at a degraded quality, and therefore is considered consumptive use. Water consumption includes evaporative losses from establishment of hydroelectric dams but does not include the water passing through the turbine, since that water is not removed from its source. The hydropower in the electricity mix (approximately 47% of overall grid mix) drives the overall water depletion impacts.[244] Water depletion associated with wood pellets is also due to electricity usage during pelletization. Water depletion impacts are also notable for sugarcane ethanol, as irrigation is required for the cane production. Some water depletion impacts are also seen for the biogas to maintain the digester, but these are negligible when compared to the evaporative losses from hydropower in the electricity grid. Water depletion impacts are negligible for the traditional biomass fuels (i.e. firewood), which are not irrigated. Because the water content of these fuels comes from the atmosphere as rainfall, the water released back to the atmosphere when the biomass is dried or combusted is not considered consumptive use.

Table A-48. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (Guatemala)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	**Processing**	**Distribution**	**Use**	**Total**
Unprocessed Solid Biomass	Firewood	0	0	0	0.60	0.60
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0	5.6E-04	0.73	0.74
	Charcoal Briquettes from Bamboo	0	0	5.6E-04	0.73	0.74
	Non-Carbonized Briquettes from Sawdust	0	0	5.8E-04	0.42	0.42
	Non-Carbonized Briquettes from Crop Residues	0	0	4.5E-06	0.069	0.069
	Wood Pellets	0	1,961	3.4E-04	0.014	1,961
	Wood Chips	0	13.1	7.8E-06	0.29	13.4
Liquid/Gas	Ethanol from Sugarcane	243	5.87	6.37	0	255
	Ethanol from Wood	0	4.35	9.7E-05	0	4.35
	Biogas from Dung	0	16.3	0	0	16.3
	LPG	7.72	56.2	75.1	0	139

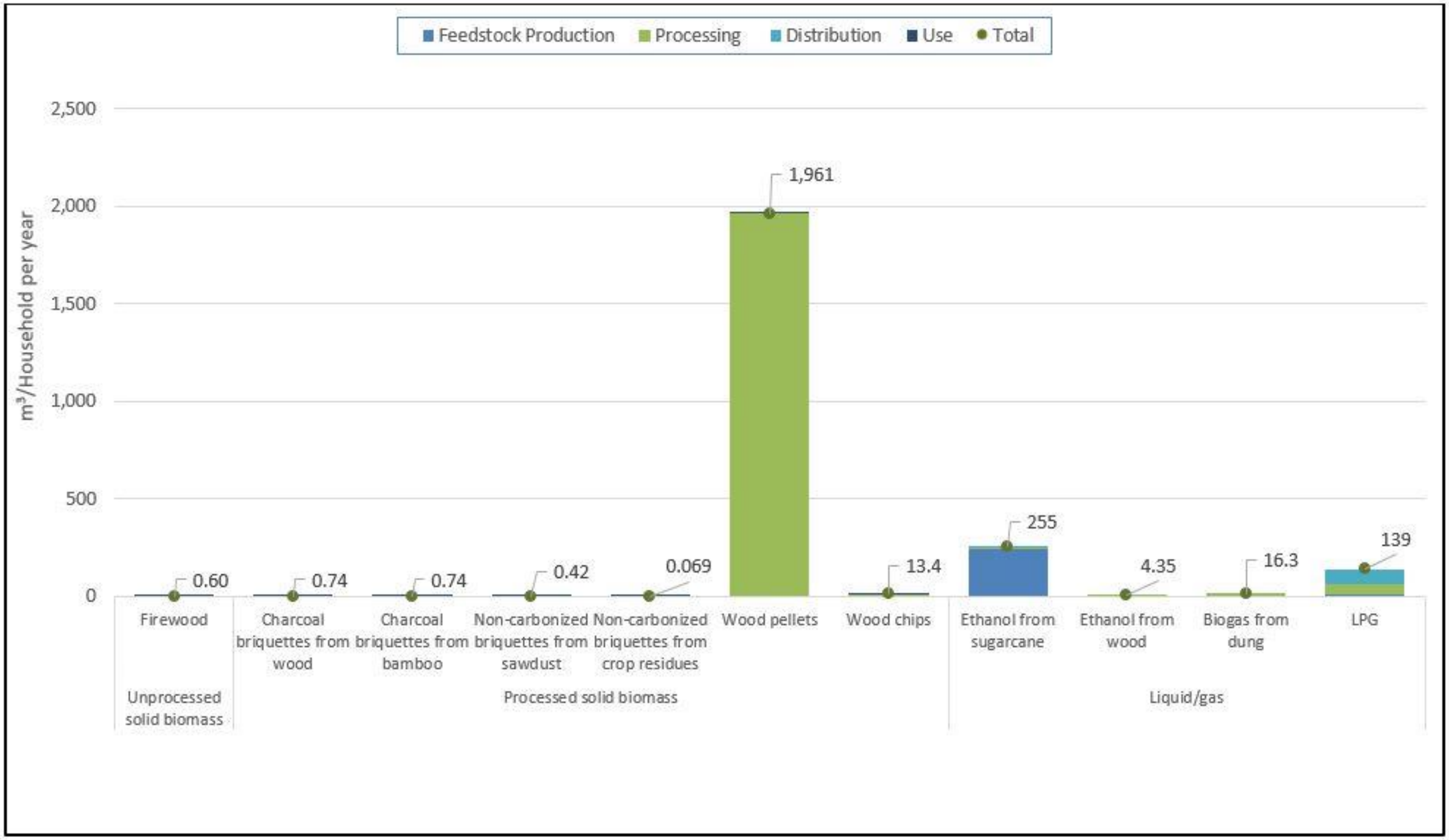


Figure A-44. Water Depletion Impacts (m³ H_2O) for Cooking Fuel Types (Guatemala)
To produce, distribute and use cooking fuels by a single household per year

A.5.2.8 Terrestrial Acidification Potential

Table A-49 and Figure A-45 show the terrestrial acidification potential impact results for fuels in Guatemala by life cycle stage. Terrestrial acidification quantifies the acidifying effect of substances on their environment. Important contributing emissions include SO_2, NO_x, and NH_3. Electricity usage for pelletization drive biomass pellet acidification impacts. Sulfur dioxide emissions from coal in the electricity grid (13% of electricity grid mix in Guatemala)[244] are notably higher than sulfur dioxide emissions from combustion of other fuels. Ethanol contains no sulfur, so there are no sulfur dioxide emissions, a main cause of acidification, for the ethanol cookstove use stage. No NO_x emissions data for ethanol combustion in a cookstove were available, although qualitative reports stated that ethanol combustion leads to minimal nitrogen oxide emissions. Firewood has slightly higher acidification impacts than the liquid fuels. The main contributing emissions leading to acidification potential for the firewood in Guatemala are SO_x and NO_x. For instance, NO_x leads to73% and SO_x leads to 27% of the firewood acidification impacts, respectively. Distribution acidification impacts in Guatemala are highest for transportation of the carbonized and non-carbonized briquettes since a greater mass of input fuel for the solid biomass is required to be transported a longer distance given the proximity of end users to forests in Guatemala. Distribution impacts are also notable for sugarcane ethanol, as the sugarcane ethanol is assumed to be transported from Brazil, the world's largest sugarcane ethanol producer (Appendix B provides detailed discussions of the model's transportation parameters). The lowest overall acidification impacts are seen for biogas. Because land applied digested sludge from biogas production is used by another product system, it is considered to be outside the system boundaries for this analysis; however, it is possible that this land applied digested sludge could lead to emissions of ammonia, an acidifying substance.

Table A-49. Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (Guatemala)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	8.06	8.06
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.025	0.77	3.13	3.93
	Charcoal Briquettes from Bamboo	0	0.025	0.77	3.20	4.00
	Non-Carbonized Briquettes from Sawdust	0	0	0.77	6.02	6.80
	Non-Carbonized Briquettes from Crop Residues	0	0	0.0059	1.21	1.22
	Wood Pellets	0	1.63	0.46	0.53	2.61
	Wood Chips	0	0.32	0.010	3.87	4.20
Liquid/Gas	Ethanol from Sugarcane	2.49	0.10	0.76	0	3.35
	Ethanol from Wood	0	1.14	0.13	0	1.27
	Biogas from Dung	0	0	0	1.66	1.66
	LPG	0.27	1.14	0.41	1.81	3.63

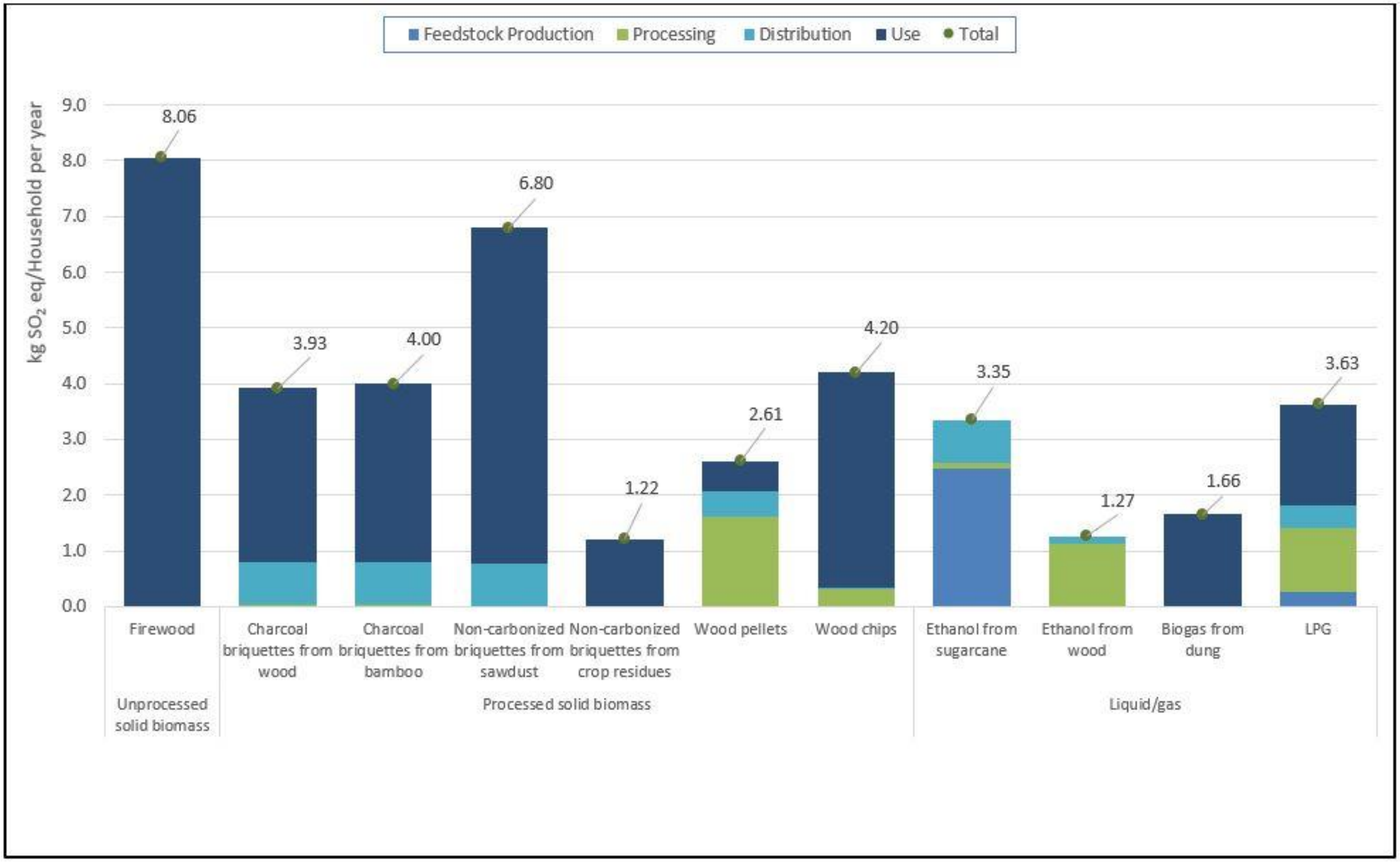


Figure A-45. Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (Guatemala)
To produce, distribute and use cooking fuels by a single household per year

A.5.2.9 Freshwater Eutrophication Potential

Table A-50 and Figure A-46 provide the freshwater eutrophication potential impact results for fuels in Guatemala by life cycle stage. Eutrophication assesses the impacts from excessive load of macro-nutrients to the environment and eventual deposition in freshwater, which can result in algal blooms, oxygen depletion, and fish kills. Pollutants contributing to this category are all P based (e.g. phosphate, phosphoric acid, phosphorus). Firewood and charcoal briquettes result in the highest eutrophication potential impacts. This is due to the much larger ash quantity produced from Firewood and charcoal briquettes compared to all other fuels. The ash from these wood fuels, which contains phosphorus is assumed to be land applied, which leads to soil emissions and eventual runoff into freshwater. While impacts are comparably smaller for ethanol, there are some minimal eutrophication impacts occurring from use of phosphorus based fertilizer in sugarcane production. There are no eutrophication impacts associated with biogas. Application of the digested sludge from the biogas system would likely lead to some eutrophication impacts, but utilization of this useful co-product is outside the system boundaries of this study. The digested sludge impacts are allocated to the product system it serves (i.e. nutrients for crop production). Impacts from fossil based fuels and wood pellets are minimal compared to the charcoal briquettes and firewood. The non-carbonized processed biomass fuels have slightly lower eutrophication potential impacts than charcoal briquettes and firewood. Because processed biomass burns more efficiently than unprocessed biomass, less fuel must be burned, leading to an overall lower quantity of ash produced.

Table A-50. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (Guatemala)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	1.95	1.95
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0	6.4E-07	2.36	2.36
	Charcoal Briquettes from Bamboo	0	0	6.4E-07	2.36	2.36
	Non-Carbonized Briquettes from Sawdust	0	0	6.6E-07	1.36	1.36
	Non-Carbonized Briquettes from Crop Residues	0	0	5.1E-09	0.22	0.22
	Wood Pellets	0	0.020	3.9E-07	0.044	0.064
	Wood Chips	0	0.0019	9.0E-09	0.94	0.94
Liquid/Gas	Ethanol from Sugarcane	0.12	7.8E-04	8.9E-04	1.7E-05	0.13
	Ethanol from Wood	0	3.4E-05	1.1E-07	1.7E-05	5.1E-05
	Biogas from Dung	0	0	0	0	0
	LPG	0.012	0.010	0.0013	0	0.024

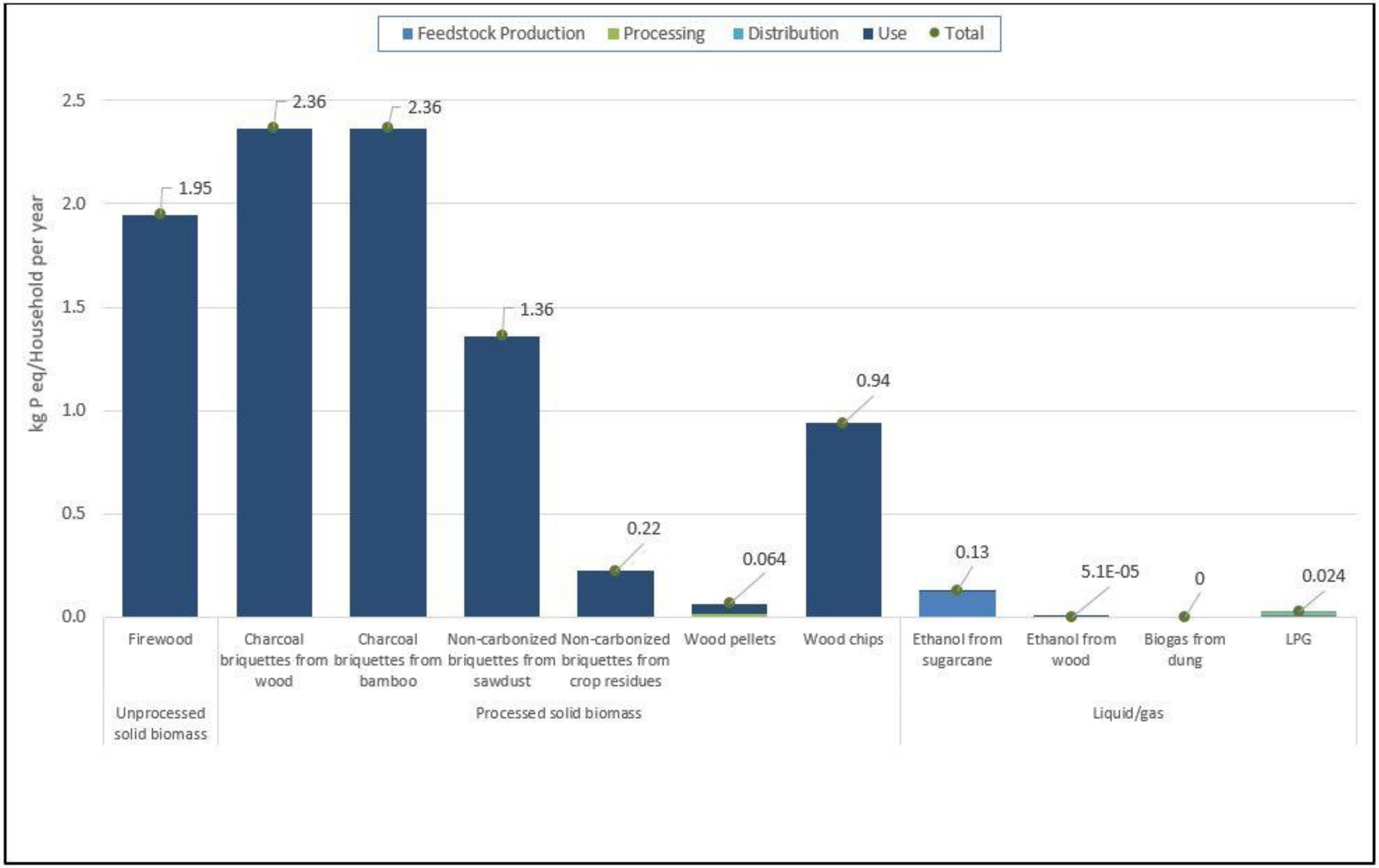


Figure A-46. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (Guatemala)
To produce, distribute and use cooking fuels by a single household per year

A.5.2.10 Photochemical Oxidant Formation Potential

Table A-51 and Figure A-47 present the photochemical oxidant formation potential impact results for fuels in Guatemala by life cycle stage. The photochemical oxidant formation (i.e. smog formation) results are an indicator of the potential for formation of reactive substances that cause harm to human health and vegetation. Results are characterized here to kg of non-methane volatile organic compounds (NMVOC) eq. Some key emissions for cookstove fuel systems that contribute to photochemical oxidant formation include carbon monoxide, methane, nitrogen oxides, NMVOCs, and sulfur dioxide. Firewood, followed by charcoal briquettes and non-carbonized briquettes from sawdust, leads to the greatest photochemical formation impacts. For charcoal briquettes, impacts are split between the fuel processing stage (carbonization in a kiln) and the use stage. Photochemical oxidant formation impacts are relatively small for the liquid fuels and biogas.

Table A-51. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (Guatemala)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	362	362
Processed Solid Biomass	Charcoal Briquettes from Wood	0	207	1.32	78.6	287
	Charcoal Briquettes from Bamboo	0	207	1.32	78.6	287
	Non-Carbonized Briquettes from Sawdust	0	0	1.33	271	273
	Non-Carbonized Briquettes from Crop Residues	0	0	0.010	16.3	16.3
	Wood Pellets	0	1.83	2.1E-05	1.60	3.43
	Wood Chips	0	0.55	0.018	175	176
Liquid/Gas	Ethanol from Sugarcane	11.9	0.027	0.58	0.97	13.5
	Ethanol from Wood	0	1.97	0.22	0.97	3.16
	Biogas from Dung	0	0.058	0	1.72	1.78
	LPG	0.30	0.78	0.33	7.87	9.27

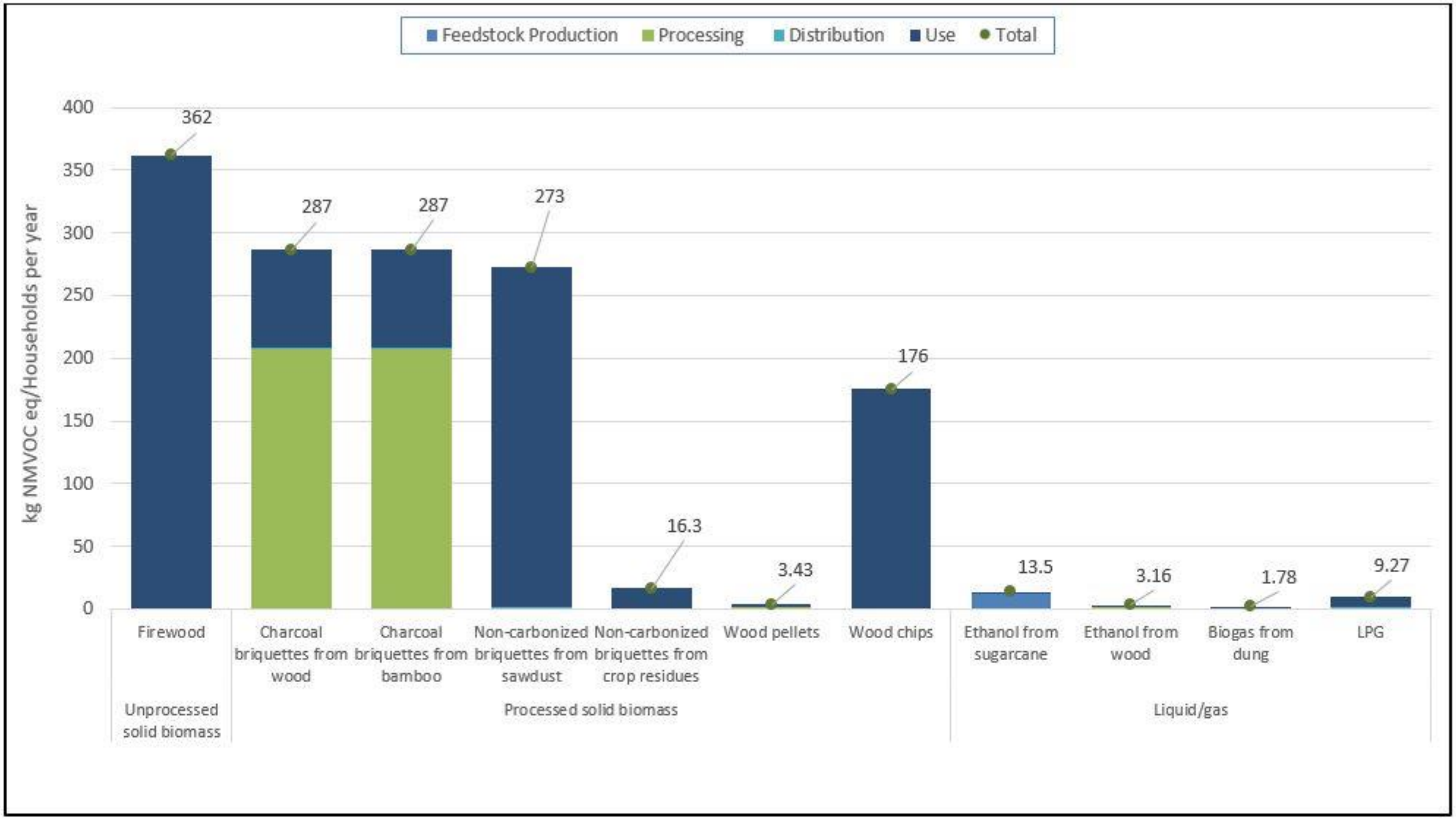


Figure A-47. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (Guatemala)
To produce, distribute and use cooking fuels by a single household per year

A.5.3 Economic Indicators for Guatemala

A.5.3.1 Fuel Use

Figure A-48 shows the shares of the population in Guatemala using various types of fuel as their primary cooking fuel. Just over 60 percent of the population relies on biomass (primarily firewood), while about 37 percent use LPG. LPG is more commonly consumed in urban areas, with 75 percent of urban households and only 25 percent of rural households using LPG.[245] Other fuels, such as charcoal and electricity make up only a combined 1.8 percent of the fuels used.[246,247,248] Ethanol, non-carbonized wood briquettes, non-carbonized crop residue briquettes, wood chips, wood pellets, and biogas are not typically used for cooking in Guatemala (the latter because the average family doesn't have enough livestock).[249]

A pipeline that will bring natural gas from Mexico to Guatemala is scheduled to be completed in 2016.[250,251] If the infrastructure for households to use this fuel for cooking is subsequently put in place, this could change the fuel landscape in the future.

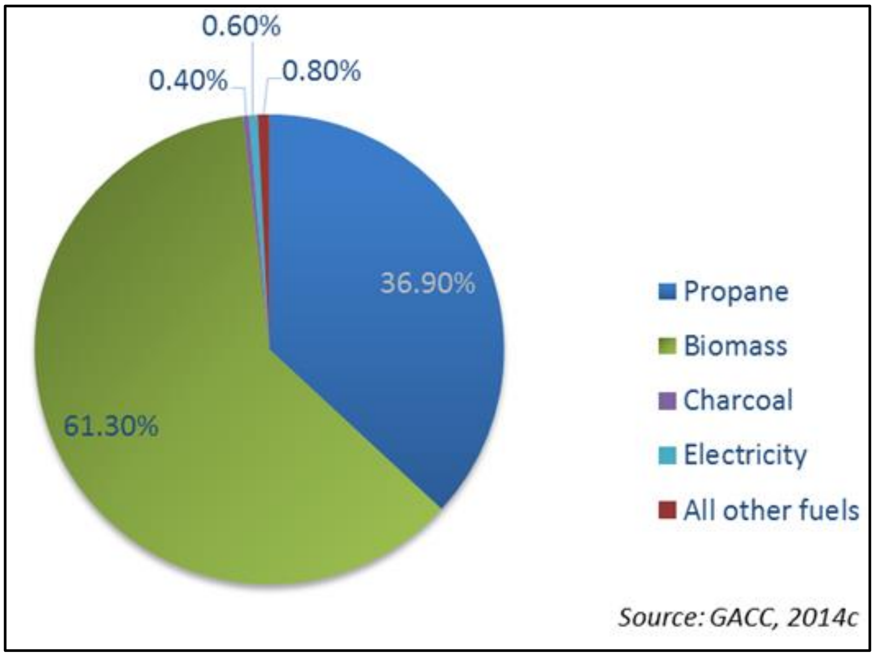


Figure A-48. Current Cooking Fuel Mix in Guatemala

A.5.3.2 Fuel Imports, Exports, Production, and Demand in Guatemala

Table A-52 shows the levels of imports, exports, production, and demand (assumed to be equal to current consumption) of several fuels in Guatemala. The data on total and household demand do not differentiate between fuel use for cooking and fuel use for other purposes such as heating. Most of Guatemala's LPG is imported. Net imports of LPG are 247,000 tonnes (351,000 tonnes of imports minus 104,000 tonnes of exports). Although specific data on production are not available, this suggests that Guatemala produces only about 13,000 tonnes (260,000 tonnes of demand minus 247,000 tonnes of net imports). About 77 percent of LPG demand is by households,[252] reflecting the fact that LPG (along with firewood) is one of the two dominant household cooking fuels in Guatemala.[253, 254]

Guatemala produces about 200,000 tonnes of ethanol (primarily from molasses), most of which is exported to Europe, Central America, and Mexico, and the rest is used within Guatemala for industrial and food purposes.[255]

Guatemala produces over 19.1 million tonnes of firewood.[256] Sixteen million tonnes of this is consumed,[257] and a very small amount is exported.[258] From 2005 to 2010, Guatemala's forest area decreased at a rate of over one percent per year.[259] If this decline is not slowed or stopped, consumers will need to find alternative fuels to wood.

Other fuels are produced and consumed on much lower scales. Guatemala produces about 65,000 tonnes of wood charcoal per year. All of this is consumed domestically, and about 75 percent of that demand is by households.[260] Guatemala exports 6,882 tonnes of wood pellets per year,[261] but no data on imports, production, or demand are available.

Table A-52. Fuel Imports, Exports, Production, and Demand in Guatemala (Tonnes per Year)

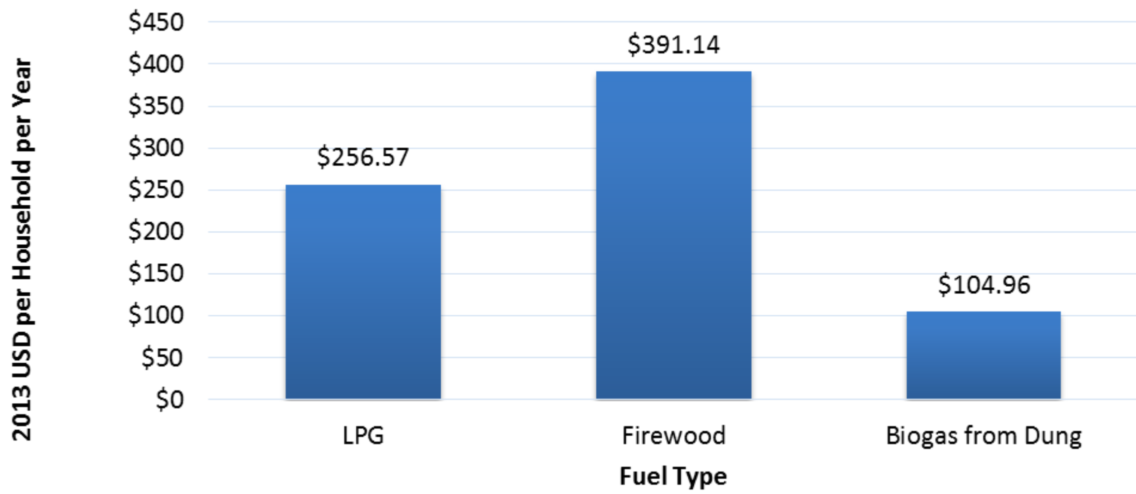
Fuel	Imports	Exports	Production	Demand		Sources
				Total	Household	
LPG	351,000	104,000	No data	260,000	200,000	UNSD, 2011
Ethanol	55	1,158	212,334	No data	No data	UNSD, 2013 Pottier, 2013
Firewood	No data	0.02	19,132,690	16,000,000	No data	UNSD, 2013 FAO, 2014 ESF, 2013
Charcoal Briquettes	No data	No data	65,000	65,000	49,000	UNSD, 2011
Wood Pellets	No data	7	No data	No data	No data	UNSD, 2013

A.5.3.3 Fuel Cost in Guatemala

Figure A-49 shows the price per household per year for the cooking fuels in Guatemala for which cost data are available. Purchased firewood has the highest average cost overall, at $392 per household per year.[262,263,264] Estimates of the share of firewood that is purchased range from 35 percent[265] to 60 percent[266], with the remainder being collected essentially free of cost. Many forested areas in Guatemala are protected, and firewood gathering is restricted,[267]although this does not necessarily prevent firewood gathering. It is estimated that the amount of firewood collected illegally is 400 times the amount collected with a wood license.[268] As in other countries, deforestation is an issue and could continue to drive up the price of firewood. [269]

The second most expensive fuel in Guatemala is LPG, at $257 per household per year. While LPG is less expensive on an annual basis than firewood, it cannot always be purchased in small or partially-filled cylinders, which means that it can be difficult for low-income households to afford. The recent introduction of 12-pound cylinders may partially alleviate this problem.[270]

The least expensive fuel is biogas produced from animal dung, where the digester has an annualized cost of $105 per household per year[271] (although, as noted in Section A 5.3.1, most families do not have enough livestock to make this option feasible).[272]



Note: No data available for fuel types not included.

Sources: ESF, 2013; Taylor, et al., 2011; Wang, et al., 2013; Matthews & Zeissig, 2011; WISIONS, 2014

Figure A-49. Fuel Cost Indicator for Cooking Fuels in Guatemala

A.5.4 Social Indicators for Guatemala

A.5.4.1 Government Policies/Programs

Although limited information is available from Guatemala's government regarding their promotion of or resistance to specific cookfuels, improved cookstove adoption is promoted through the Ministry of Health and two health-based organizations (Centro de Estudios Para el Desarrollo y la Cooperación (CEDEC) and Asociación Mujeres Ixchel), indicating government support for clean cooking methods. While not directed at household-level energy consumption, carbon financing (through Clean Development Mechanism credits) has been used to develop at least two biogas generation projects.[273]

Indirect (and especially wood-based) cookfuel insights are available through the numerous government initiatives that have sought to increase the adoption of improved cookstoves and promote the stewardship of Guatemala's forests.

- National Energy Policy (2013-2027). Outlines a plan to install 100,000 clean biomass stoves. Also provides for training in efficient wood use, the reduction of industrial firewood consumption (it is unclear whether this would potentially mean more wood is available for wood-based fuel manufacturers, or if pellet and briquette producers are considered "industry"), and the promotion of energy alternatives.

- National Strategy for the Sustainable Production and Consumption of Woodfuels (2013-2024; proposed 2012 – status unknown). Outlines a plan to distribute 100,000 improved cookstoves. Also calls for the establishment and management of at least 48,000 hectares of plantations and agroforestry systems.

- Fondo Nacional para la Paz (FONAPAZ); Fondo para el Desarrollo Indigena de Guatemala (FODIGUA); Programa Nacional de Desarrollo Rural (ProRural); Desarrollo Integral de Comunidades Rurales (DICOR); Secretaria Presidencial de la Mujer (SEPREM) (2001-2013). Various government programs that distributed around 20,000 firewood stoves. The initiatives also focused on rural development, poverty alleviation, and in the case of SEPREM, women's health. These programs were not systematized and lack complete documentation.

- Readiness Preparation Proposal (2013). Plan outlining steps Guatemala will take between 2013-2017 to prepare for a REDD+ regime (the UN-led program for Reducing Emissions from Deforestation and Forest Degradation). Various pilot programs aimed at environmental stewardship have already been implemented in forest reserves and National Parks. The National Strategy for Reducing Deforestation is being developed to design and implement REDD+ activities.

- National Policy on Woodfuels (proposed 2011). Promotes the efficient use of firewood at the domestic- and SME-level through the use of energy-efficient technology. Also calls for sustainable firewood cultivation through forestry programs.

- Fondo de Inversion Social (1996-2008). Distributed approximately 160,000 plancha (improved wood-burning) stoves.

- The 2020 Central American Sustainable Energy Strategy (2007). Effort across Central America to promote improved cookstoves in 1,000,000 households and reduce woodfuel consumption by 10 percent.

- Tezulutlan project (1998-2001). Distributed more than 4,000 improved cookstoves in Baja Verapaz through various health and nutrition programs.[274]

These initiatives highlight both the government of Guatemala's commitment to promoting clean cooking methods and the extent to which clean cooking policies can complement ongoing sustainability efforts.

A.5.4.2 Supply & Access Challenges

The most widely-used and available cookfuel in Guatemala is firewood. Although anywhere from 35 percent[275] to 60 percent[276] of people who use firewood purchase it, the industry does not enjoy commercial stability through robust supply chains; rather, the fuel is gathered, and at times procured illegally, from municipal forests in an organized fashion and then sold to end-users.[277] Such informal modes of supply and distribution are growing less and less sustainable in the face of deforestation—forest land is decreasing at a rate of approximately 1.5 percent per year over recent years[278]—and efforts to protect municipal forests are disrupting these ad hoc supply chains even more.[279] Unsustainable biomass management is likely to have an even greater impact on the 45 percent of rural (and 10 percent of urban) Guatemalans who rely on the firewood they collect themselves.[280] Underscoring the immediacy of the potential impacts, one study that found there is already an annual firewood deficit of more than 5 million tons of dry wood equivalent.[281]

Alternatives to firewood are not reliably available. Charcoal briquetting infrastructure is not in place (some wood is charred, though not as briquettes), bamboo supplies (when used for cooking) are burned raw, and the production of noncarbonized briquettes from crop residues is hampered by feedstock limitations resulting from farmers burning the leaves of their crops before harvest to facilitate the use of combines. Biogas from animal dung and ethanol both face reliability challenges, as well. There have been few initiatives to promote biogas use at the household level since most people do not have enough livestock to run the digester in an efficient manner. Although ethanol is produced domestically (primarily from molasses), the vast majority of it is exported to Europe, Central America, and Mexico. The remainder is used within Guatemala for industrial and food purposes.[282] LPG use is established in urban and peri-urban communities, however, due to cost and transportation challenges, the fuel is not reliably available in rural settings.[283] In fact, one study found that due to delays in delivery, households normally keep two LPG cylinders on hand to ensure uninterrupted use,[284] underscoring the cost and logistical challenges to obtaining the fuel in non-urban areas.

A.5.4.3 Distribution & Adoption Challenges

The two leading challenges to the adoption of target fuels in Guatemala relate to cost. In rural areas, where households have limited access to cash, fuel is either collected or purchased in small—at times per-meal—quantities.[285] Both of these trends lead to a reliance on firewood, as it tends to be the most convenient biomass to collect manually and can be purchased in any quantity.[286] In urban areas, where incomes are higher and fuel stacking (the use of multiple fuels) dominates, households tend to use a combination of liquid and gaseous fuels.[287] This income divide is corroborated by a study which found that LPG selection increased with household expenditure and the highest levels of education attained by household members.[288]

A.5.4.4 Protection & Safety

For purchased fuels considered in this analysis (e.g., LPG or ethanol), no safety issues during the purchase of the fuels were found within the literature. Collection of crop residues usually occurs somewhat close to the household, and no safety issues were found in the literature. Anywhere from 40 percent[289] to 65 percent[290] of firewood in Guatemala is collected, and, although no data were found indicating the presence of safety risks when it is gathered manually, certain hazards such as encounters with venomous snakes or accidents occurring when carrying heavy loads cannot be ruled out. Despite the lack of data regarding perceived safety risks among the target fuels, anecdotal information suggests safety concerns are not a primary driver of new fuel adoption in Guatemala. In fact, safety ranks as only the fourth-highest priority among potential users of new fuels, behind such things as convenience and comfort.[291]

A.5.4.5 Time & Drudgery

In Guatemala, men and women share the firewood collection burden with men spending around two hours per day and women spending around one and a half hours per day collecting.[292] This pattern may change, however, as more communities—in response to biomass shortages—switch to using dedicated wood gatherers (who sell their goods at depots) to meet their firewood needs.[293] Although men are primarily responsible for fuel collection, women handle more than 90 percent of the cooking, spending on average between three and four hours per day cooking over wood stoves.[294,295,296]

Although collection- and cooking-time savings data were not available for alternative fuels in Guatemala, observations from other phase one countries indicate that substantial time savings opportunities are available. For example, the acquisition of commercial fuels such as LPG and wood-based charcoal briquettes tends to take less time than the manual collection of firewood, and cooking over efficient modern fuels tends to reduce time spent in the kitchen relative to cooking over wood fires. Quantified projections—which must take into account variables such as the proximity of fuel retail locations and the heating demands of cooking traditional foods—were not possible based on the consulted literature.

A.5.4.6 Income Earning Opportunities

Given the newness of the feedstock-fuel combinations in the present study, limited information regarding the income earning opportunities associated with specific cookfuels is available. Some general observations can be made, however, for LPG and ethanol. Due to financial constraints, users of traditional fuels in Guatemala are often forced to buy fuel in weekly, daily, and sometimes even per-meal increments. Purchasing traditional fuels such as wood in such small quantities is cost-ineffective (consumers lose out on bulk pricing and must absorb the opportunity cost of repeated small purchases) but is often the only option.

As LPG and ethanol are increasingly produced in smaller cylinders and bottles, six-to-seven pounds and one liter, respectively, more consumers—especially those in rural areas—can afford to switch from wood to these fuels, increasing business for sellers of LPG and ethanol.[297] One factor potentially mitigating this trend, however, is the likely increase of distribution costs incurred by retailers extending their LPG and ethanol infrastructure (refill, maintenance, and replacement service coverage area) to meet the demand of rural users. In other words, if the increase in market share generated by access to rural markets does not offset the increase in costs associated with servicing them, liquid and gaseous fuel enterprises might need to increase the cost they charge to end-users or scale back the geographic scope of their operations altogether – either of which would attenuate the income earning opportunities associated with smaller-sized canisters and cylinders.

Another income earning opportunity in Guatemala is in the wood-based charcoal briquette industry. As transportation often represents a sizeable share of the final fuel cost passed on to consumers, the ability to produce briquettes out of sawdust from local lumberyards would provide an opportunity for manufacturers to cut costs and substantially improve their profit margins.[298]

Although it has yet to be implemented at the household level, a partnership between Alterna and WISIONS produced a biogas system that runs on manure and foodscraps. Successful promotion of the biogas system has relied on both the subsidization of upfront costs and raising awareness about the aggregate time and energy savings possible with nontraditional fuels. That is, Alterna and WISIONS helped users understand that even though the daily operation and maintenance of biogas systems might initially exceed the level of effort they are used to expending on fuel collection, they will achieve substantial savings over time (usually around $440 in fuel costs per year for small-scale ventures).[299]

A.5.4.7 Potential Increase of Skills for Women

According to the Global Alliance for Clean Cookstoves 2013 Results Report, the clean cookstove industry in Guatemala currently has 176 employees (18 percent of whom are women) and 39 microentrepreneurs (49 percent of whom are women).[300] Men in Guatemala may handle the physical side of fuel production and distribution, but there are opportunities for women in sales and the less laborious aspects of fuel production.[301] Cultural and economic barriers inhibiting women’s entrance into the cookfuel market are potentially less pronounced in

Guatemala than in other Phase One countries,[302] though they are still assumed to be present. The only sector for which fuel-specific insights are available is LPG. Although the LPG market in Guatemala is unstable, the turbulence presents an opportunity for women who are involved in the industry to increase public awareness of negative market practices and advocate for better regulations. For example, GenteGas plans to use a woman-to-woman salesforce to promote LPG use and raise awareness about health, safety, and financial literacy.[303]

Africa

A.6 Detailed Results for Nigeria

A.6.1 Overview of Nigeria

Nigeria is Western Africa's most populous country and ranks as the seventh most populous country in the world, with 181.8 million residents in 2015,[304] the environmental, economic, and social implications of cooking fuel use have large-scale effects. The choice of cooking fuel affects not only the persons in the household using the fuel (who are exposed to emissions associated with combustion of the fuel), but the issues of adequate supply, accessibility, and cost must also be taken into account, as well as wider environmental consequences associated with the life cycle of the fuel (including resource consumption, emissions, and wastes associated with fuel feedstock acquisition, processing, distribution, and combustion).

Over 70 percent of the population use biomass fuel (primarily firewood) for cooking.[305,306,307,308] The North Central region has the highest dependency on firewood.[309] The remaining households primarily use kerosene, although small percentages of the population use LPG, coal, charcoal, electricity, dung, and other fuels.[310] Fuels such as ethanol, carbonized and non-carbonized wood briquettes, and biogas may be used on a very limited basis.[311] The majority of kerosene dependent households are located in the southern regions. [312]

As in other countries, fuel use patterns vary with the user's income level and whether they live in an urban or rural setting. The portion of Nigeria's population living in rural and urban areas is about equal at 50 percent.[313] LPG is most commonly used by high-income urban residents, wood by low-income rural residents, and a mix of wood, charcoal, and kerosene by middle-income residents in both urban and rural areas.[314] While individual user preferences vary, a survey of Nigerians found that a majority of respondents considered kerosene the most desirable fuel, primarily due to its ease of use.[315]

Adequate supply of fuel resources is an important consideration, as there may not be adequate feedstocks to sustainably support current or increasing levels of use of certain fuels. For example, demand for firewood must be balanced against the trends in forest area and biomass regeneration per hectare. Nigeria has shown an overall trend of over 3 percent decrease in forest land per year over recent years.[316] Deforestation is more acute in the north, which is part of the Sahara desert.[317] Logging, subsistence agriculture, where a farmer grows or raises just enough food to feed their family, and the collection of firewood are leading causes of forest clearing in Nigeria.[318] Some regions are experiencing desertification where dry lands become increasingly arid. Nigeria is losing about 1,355 square miles of cropland and rangeland due to desertification each year.[319] This problem affects each of the 11 states of northern Nigeria.[320]

Fuel cost is another key issue. The Word Bank reports that in 2010, 62 percent of Nigeria's population is below the international poverty line of $1.25 per capita per day.[321] Fuel choice is also affected by the perception of safety associated with acquisition and use of the fuel, as well as safety perceptions about the type of stove used with each fuel.

Finally, cultural issues around food and cooking fires are an important consideration. The flavor imparted to certain foods by specific cooking fuels can be very important to consumers, leading to resistance to changing fuel types. Households across Nigeria generally eat similar foods and have the same cooking habits; however, urban households are moving away from traditional cooking for speed and convenience. [322] Rural households use outdoor stoves when using firewood to avoid the smoke and to reduce fire hazards. [323] Typical foods prepared include yams and cassava which require significant boiling and preparation time. Cooking fires may serve multiple additional purposes in the home, such as providing heat or light, preserving food (by drying above or near the fire), and drying clothing. Changes to the cooking fuel or type of cookstove would likely require the household to use other fuels for these functions. Urban households usually cook in enclosed passageways and reduce cooking time by replacing yams and cassava with rice. [324]

The following sub-sections address the environmental, economic, and social considerations related to cooking fuels and stoves for Nigeria in greater detail.

A.6.2 Environmental Indicators for Nigeria

This section covers the detailed Nigeria LCA results for the ten environmental indicators assessed for each fuel. The stove thermal efficiency by fuel and the fuel heating values employed in this study to calculate the LCA results are provided in Table A-53 and Table A-54, respectively. The remainder of this section presents results for each environmental indicator.

Table A-53. Stove Thermal Efficiency Applied by Fuel for Nigeria

Fuel Type	Stove Thermal Efficiency	Sources
Firewood	14.0%	Afrane & Ntiamoah, 2012
Charcoal Briquettes from Wood	18.0%	Afrane & Ntiamoah, 2011
Charcoal Briquettes from Bamboo	18.0%	Afrane & Ntiamoah, 2011
Non-Carbonized Briquettes from Sawdust	20.3%	GACC, 2015a Urban Uganda, 2015
Non-Carbonized Briquettes from Crop Residues	31.0%	GACC, 2015a
Wood Pellets	53.0%	Jetter et al., 2012
Wood Chips	31.0%	GACC, 2015a
Ethanol from Sugarcane	53.0%	Aprovecho Research Center, 2009
Ethanol from Wood	53.0%	Aprovecho Research Center, 2009
Biogas from Dung	55.0%	Afrane & Ntiamoah, 2011
LPG	57.0%	Afrane & Ntiamoah, 2011

Table A-54. Fuel Heating Values for Nigeria

Fuel Type	HHV (MJ/kg)	Sources
Firewood	14.0	Afrane & Ntiamoah, 2012
Charcoal Briquettes from Wood	25.72	Afrane & Ntiamoah, 2011
Charcoal Briquettes from Bamboo	25.72	Afrane & Ntiamoah, 2011
Non-Carbonized Briquettes from Sawdust	17.6	Davies et al., 2013
Non-Carbonized Briquettes from Crop Residues	17.6	Simonyan & Fasina, 2013 FAO, 2015
Wood Pellets	17.94	Singh et al., 2014

Table A-54. Fuel Heating Values for Nigeria

Fuel Type	HHV (MJ/kg)	Sources
		Jetter et al., 2012
Wood Chips	14.0	Afrane & Ntiamoah, 2012
Ethanol from Sugarcane	28.3	Aprovecho Research Center, 2009
Ethanol from Wood	28.3	Aprovecho Research Center, 2009
Biogas from Dung	17.71	Afrane & Ntiamoah, 2011
LPG	45.84	Afrane & Ntiamoah, 2011

A.6.2.1. Total Energy Demand

Table A-55 and Figure A-50 display the total energy demand impact results for fuels in Nigeria by life cycle stage. Total energy demand sources consist of non-renewable fuels (natural gas, petroleum, coal, and nuclear) and "renewable" fuels (e.g. biomass, hydro). Energy demand tracks all energy inputs across the life cycle of the fuel, with energy impacts shown at the point of use of the relevant fuel.

The total energy demand results are largely a function of the fuel heating value and thermal efficiency of the fuel and stove combination (Table A-53 and Table A-54). Stoves with higher efficiencies (e.g., LPG, biogas, ethanol, and biomass pellets) have a lower total energy demand overall, because more of the heating value of the fuel is converted into useful cooking energy and therefore less fuel must be produced, transported, and burned to deliver the same amount of cooking energy.

A number of observations can be made regarding energy results for the various types of fuels. For sugarcane ethanol, the feedstock energy results include not only the energy value of the sugar that is converted to ethanol but also the energy content of the bagasse, which provides the majority of energy used to process the sugarcane to ethanol. A co-benefit of ethanol production is the production of electricity, which may be exported. As discussed in the Appendix B methodology, this model employs the cut-off allocation methodology; therefore, a credit is not given here to the sugarcane or wood ethanol for exported electricity, so the energy demand impacts for ethanol should be considered as the upper bounds for these fuel types.

For wood fuels, the wood pellets and wood chips have a lower total energy demand than traditional firewood. Wood chips and wood pellets typically have a lower moisture content, greater energy content, and greater surface area than the traditional solid biomass, which allows the fuel to combust more efficiently. It is also more common to see improved cookstoves, which have higher stove thermal efficiencies, used in combination with the wood chips and wood pellets in Nigeria.

For briquettes, the energy demand impact for the carbonized briquettes from wood and bamboo is relatively higher compared to other fuels due to the lower stove efficiencies for metal charcoal briquette stoves in Nigeria and the charcoal kiln energy impacts. That is, additional energy is consumed when burning firewood at the kiln to produce charcoal prior to charcoal briquette utilization in a cookstove. Similarly, in processing the commercially made non-carbonized sawdust briquettes (3% of sawdust briquettes are assumed to be produced commercially in Nigeria), sawdust is combusted to remove the moisture content of the briquettes, which contributes to the relatively higher total energy demand of the sawdust briquettes compared to other non-carbonized processed biomass fuels. The remaining 97% of sawdust briquettes are modeled as pressed manually and dried naturally to 10% moisture content. This requires 1.5 kg wood input to each 1 kg briquette, assuming a 40% moisture content of the original greenwood.[173]

Overall, liquid and gas fuels as well as processed solid biomass fuels not requiring additional combustion of solid fuel for processing (e.g., wood pellets) lead to the lowest overall total energy demand impacts.

Table A-55. Total Energy Demand (MJ) for Cooking Fuel Types (Nigeria)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed solid biomass	Firewood	0	0	0	114,855	114,855
Processed solid biomass	Charcoal briquettes from wood	0	232,903	0.11	89,364	322,267
	Charcoal briquettes from bamboo	0	224,714	0.11	89,364	314,079
	Non-carbonized briquettes from sawdust	0	43,344	0.11	79,239	122,583
	Non-carbonized briquettes from crop residues	0	116	0.0013	58,029	58,145
	Wood pellets	0	12,809	1.49	30,350	43,160
	Wood chips	0	454	0.043	51,889	52,343
Liquid/gas	Ethanol from sugarcane	527	12,601	435	30,350	43,912
	Ethanol from wood	0	3,730	0.43	30,350	34,080
	Biogas from dung	0	0	0	28,483	28,483
	LPG	16,106	66,514	237	28,220	111,077

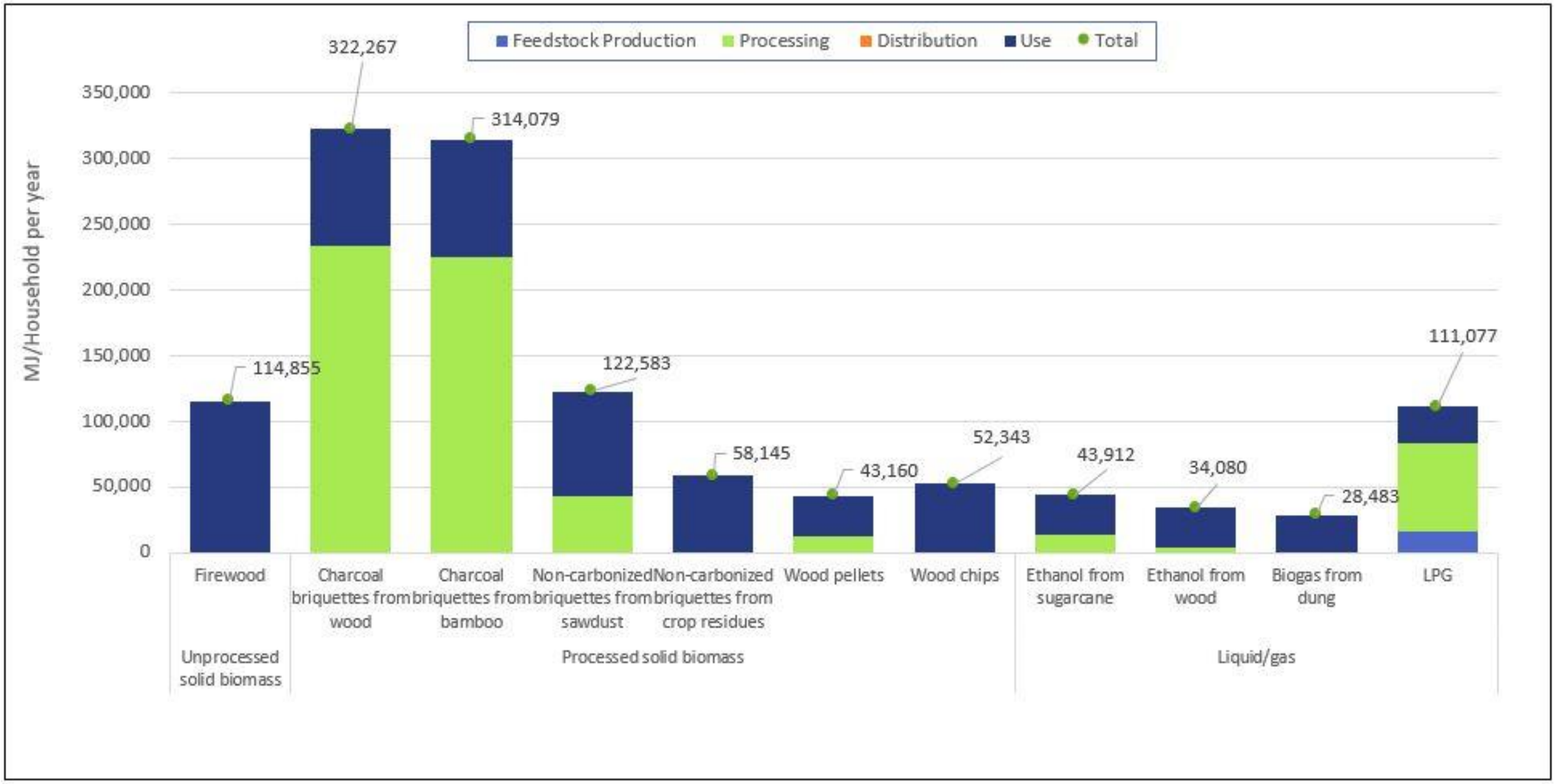


Figure A-50. Total Energy Demand (MJ) for Cooking Fuel Types (Nigeria)
To produce, distribute and use cooking fuels by a single household per year

A.6.2.2 Net Energy Demand

Table A-56 and Figure A-51 illustrate the net energy demand impact results for fuels in Nigeria by life cycle stage. Net energy demand is calculated in the same way as total energy demand, with the final energy delivered to the cooking pot deducted from the results. The net energy indicator is, therefore, the additional energy required for the life cycle of the cookstove fuel beyond what is delivered to the consumer for cooking purposes. For Nigeria, 44.1 MJ of cooking energy are consumed per household per day, which equates to 16,086 MJ per household per year.[325] Utilization of unprocessed firewood consumes seven times more energy than is provided to the pot, as listed in the last column of Table A-56. Similar levels of net energy demand are seen for non-carbonized briquettes from sawdust, and LPG. The lowest overall net energy demand is calculated for non-carbonized briquettes from crop residues, wood pellets, wood chips, ethanol, and biogas from dung. Production, processing, distribution, and use of these less energy intensive fuels uses 0.77 to 2.61 times the amount of energy delivered to the pot. Charcoal briquettes result in the highest net energy demand due to the lower yield at the kilns in African countries as compared to countries investigated in other world regions. For Nigeria, 4.9 kg of wood are required for 1 kg charcoal output at the earth mound kiln.[326] Energy impacts are also higher for petroleum refining in Africa as compared to other world regions modeled, resulting in the notable net energy demand burdens of LPG.[327]

Table A-56. Net Energy Demand (MJ) for Cooking Fuel Types (Nigeria)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage					Net Energy Consumed: Delivered Energy
		Feedstock Production	Processing	Distribution	Use	Total	
Unprocessed solid biomass	Firewood	0	0	0	98,770	98,770	6.14
Processed solid biomass	Charcoal briquettes from wood	0	232,903	0.11	73,279	306,181	19.0
	Charcoal briquettes from bamboo	0	224,714	0.11	73,279	297,993	18.5
	Non-carbonized briquettes from sawdust	0	43,344	0.11	63,154	106,498	6.62
	Non-carbonized briquettes from crop residues	0	116	0.0013	41,943	42,059	2.61
	Wood pellets	0	12,809	1.49	14,265	27,075	1.68
	Wood chips	0	454	0.043	35,803	36,257	2.25
Liquid/gas	Ethanol from sugarcane	527	12,601	435	14,265	27,827	1.73
	Ethanol from wood	0	3,730	0.43	14,265	17,995	1.12
	Biogas from dung	0	0	0	12,397	12,397	0.77
	LPG	16,106	66,514	237	12,135	94,992	5.91

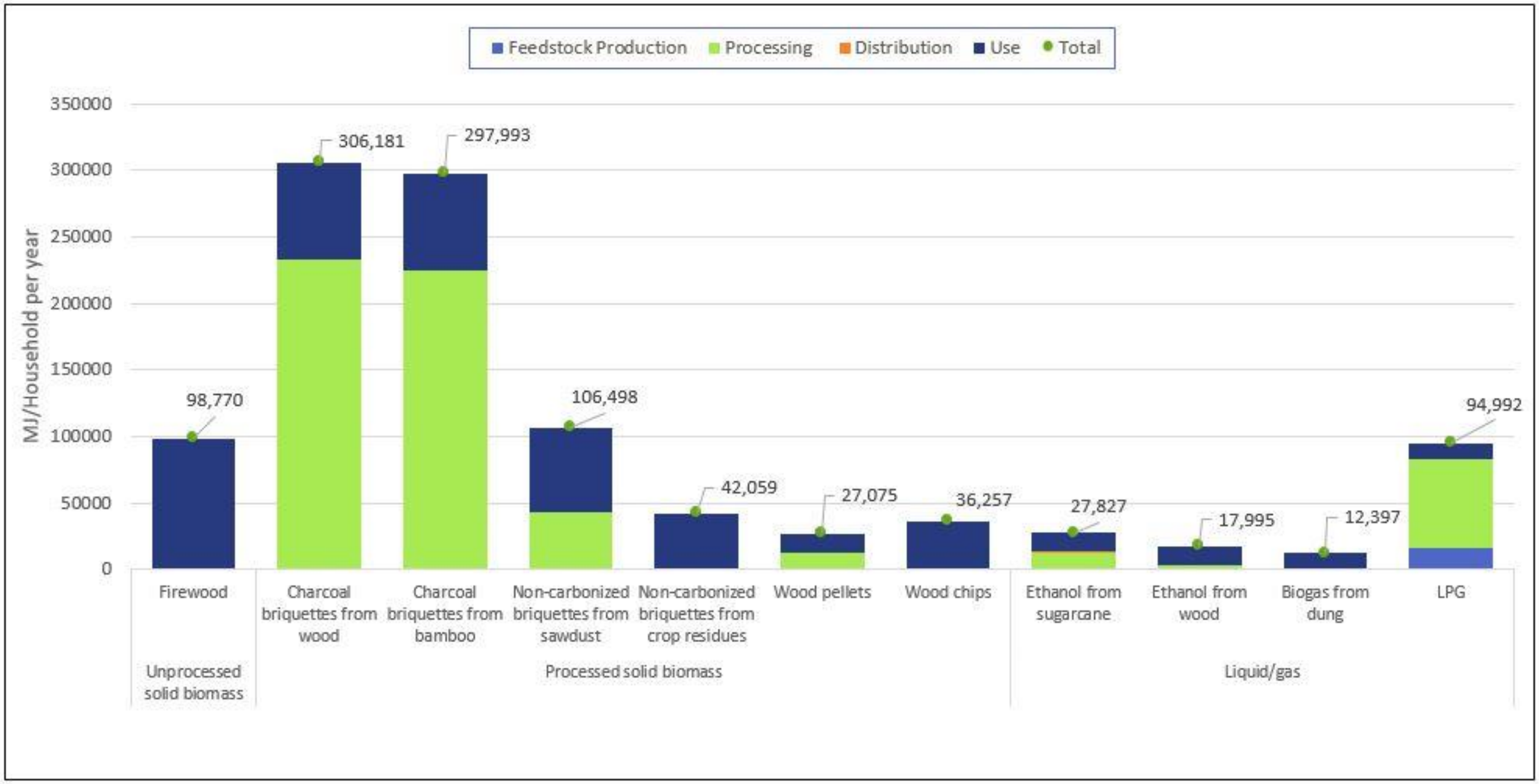


Figure A-51. Net Energy Demand (MJ) for Cooking Fuel Types (Nigeria)

To produce, distribute and use cooking fuels by a single household per year

A.6.2.3 Global Climate Change Potential (100a)

Table A-57 and Figure A-52 present the GCCP impact results for fuels in Nigeria by life cycle stage. The GCCP impact category represents the heat trapping capacity of greenhouse gases over a 100 year time horizon. Fossil fuel GCCP impacts are dominated by combustion emissions in the cookstove use stage.

Biogas GCCP impacts are primarily from methane leakage during the production of biogas in an anaerobic digester (1% of biogas escapes as fugitive emissions at the digester).[328] Sugarcane ethanol, crop residue briquettes, and charcoal briquettes from bamboo are derived from renewable biomass that removed CO_2 from the atmosphere during growth; therefore, the CO_2 emissions released from combustion of these fuels is considered carbon neutral, as discussed in detail in the Appendix B methodology. Impacts for these renewable fuels during the use phase are driven by nitrous oxide and methane emissions during cookstove use. Impacts associated with fertilizer production and emissions from application also play a role in the sugarcane ethanol overall impacts.

Based on the decreasing trend in forest area in Nigeria, all of the wood harvested for use as cooking fuel is considered unsustainably sourced, and the combustion emissions for the non-sustainable use of wood are not considered carbon-neutral. This adjustment is also applied to other wood fuels (wood-derived charcoal briquettes, wood pellets and wood chips), but not to fuels derived from wood wastes (wood ethanol and non-carbonized briquettes from sawdust). With the cut-off modeling methodology used in this analysis, wood wastes are treated as a “free” product (all burdens are allocated to the primary wood product, e.g., lumber, which is outside the scope of this study), so emissions of biomass CO_2 for fuels derived from wood waste are treated as carbon neutral. For charcoal briquettes, GCCP impacts for carbonization of the wood in the kiln are higher in magnitude than the emissions from combustion of the charcoal briquettes in a cookstove. Combustion emissions for bamboo-derived charcoal briquettes are lower than for wood-derived charcoal briquettes because bamboo is a renewable crop and all combustion emissions are considered carbon-neutral, while none of the wood combustion emissions are considered carbon-neutral, since the wood supply in Nigeria is considered non-renewable based on the decreasing forest area. All GHGs associated with the production and combustion of LPG, including CO_2 emissions from cooking, are considered fossil-derived and accounted for in the GCCP impacts.

Table A-57. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (Nigeria)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total
		Feedstock Production	Processing	Distribution	Use	
Unprocessed Solid Biomass	Firewood	0	0	0	12,929	12,929
Processed Solid Biomass	Charcoal Briquettes from Wood	0	14,964	197	9,350	24,512
	Charcoal Briquettes from Bamboo	0	3,352	197	1,427	4,976
	Non-Carbonized Briquettes from Sawdust	0	15.2	197	1,216	1,428

Table A-57. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (Nigeria)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	**Processing**	**Distribution**	**Use**	**Total**
	Non-Carbonized Briquettes from Crop Residues	0	6.68	0.098	730	737
	Wood Pellets	0	385	110	5,514	6,010
	Wood Chips	0	15.2	3.20	5,832	5,851
Liquid/Gas	Ethanol from Sugarcane	184	10.4	31.1	15.4	241
	Ethanol from Wood	0	79.0	31.6	15.4	126
	Biogas from Dung	0	6.54	0	41.4	48.0
	LPG	1,696	16.2	13.5	4,489	6,214

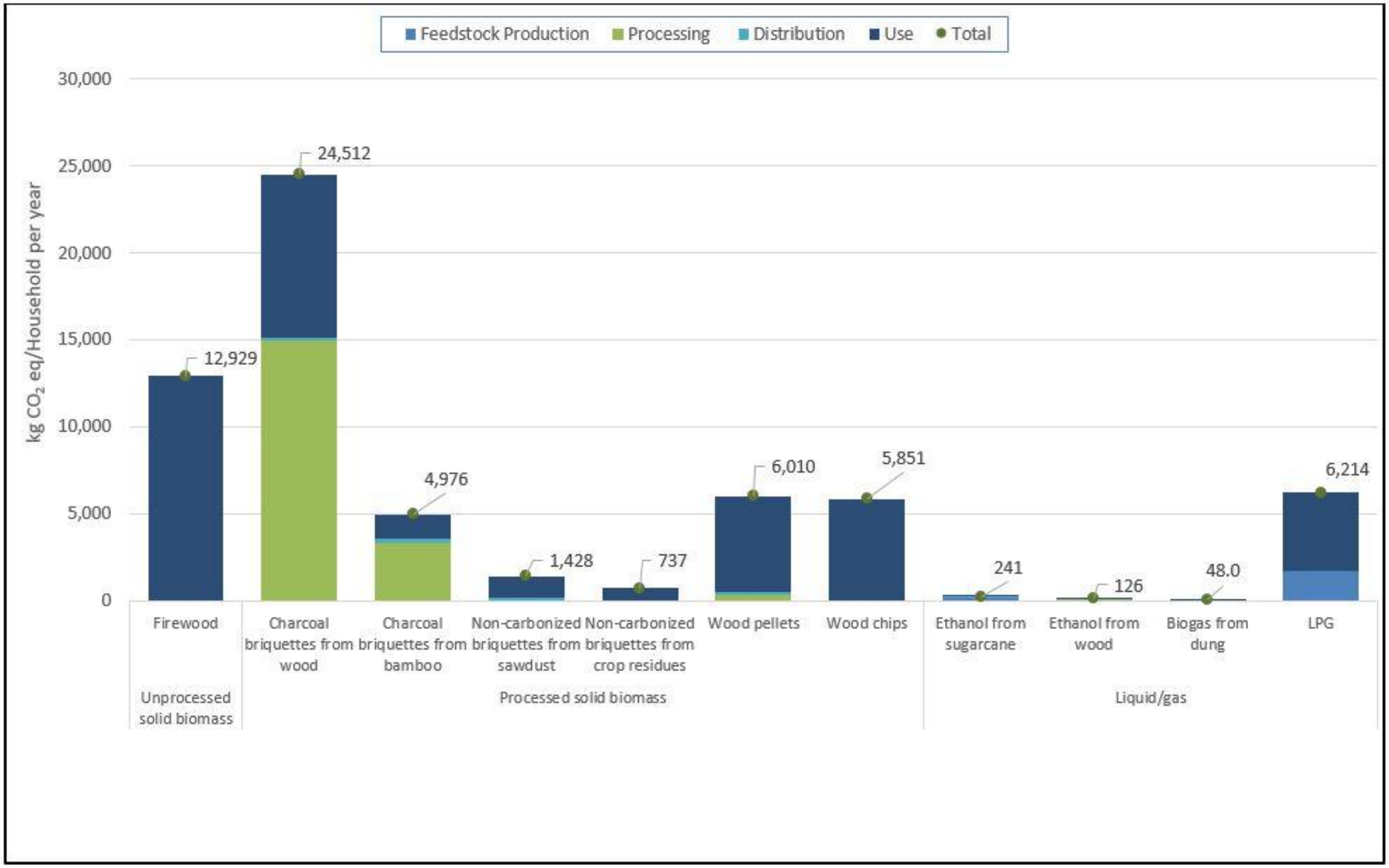


Figure A-52. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (Nigeria)
To produce, distribute and use cooking fuels by a single household per year

A.6.2.4 Black Carbon and Short-Lived Climate Pollutants

Table A-58 and Figure A-53 display the black carbon and short-lived climate pollutants impact results for fuels in Nigeria by life cycle stage. Black carbon (BC) is formed by incomplete combustion of fossil and bio-based fuels. BC is the carbon component of particulate matter (PM) with aerodynamic diameter less than or equal to 2.5 microns (PM2.5). This is the size of PM that most strongly absorbs light and thus has potential radiative forcing effects (i.e., potential to contribute to global warming). Potential climate forcing impacts resulting from BC emissions include direct, albedo (i.e., fraction of solar energy hitting the earth that is reflected), and other effects. BC is emitted with other particles (e.g. organic carbon) and criteria pollutants such as nitrogen and sulfur dioxides. Though some of these co-pollutants may exert a cooling effect on climate, the net effects of BC emissions likely contribute to global climate warming. Appendix B shows the 20 year global warming potential and black carbon equivalent values used in the results calculation. Results are presented here based on BC equivalents. The highest BC impacts are seen for charcoal briquettes, which tend to have high particulate matter emissions when processed in a kiln and also when combusted. Similarly, high emissions of particulate matter are seen for use of firewood in traditional stoves. Utilization of the liquid and gas fuels result in the lowest overall BC impacts. Some life cycle stages have negative BC equivalent impacts, which is the case when emissions of SO_x and organic carbon, pollutants with net cooling effects on the climate, are greater than the emissions of BC and other co-emitted pollutants that lead to short term warming impacts.

Table A-58. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (Nigeria)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total
		Feedstock Production	Processing	Distribution	Use	
Unprocessed Solid Biomass	Firewood	0	0	0	11.0	11.0
Processed Solid Biomass	Charcoal Briquettes from Wood	0	22.9	0.013	4.29	27.2
	Charcoal Briquettes from Bamboo	0	22.3	0.013	4.29	26.6
	Non-Carbonized Briquettes from Sawdust	0	0.062	0.013	7.62	7.70
	Non-Carbonized Briquettes from Crop Residues	0	-1.4E-04	6.6E-06	13.5	13.5
	Wood Pellets	0	-0.0065	0.0074	0.34	0.34
	Wood Chips	0	0.0036	2.1E-04	4.97	4.97
Liquid/Gas	Ethanol from Sugarcane	0.0011	-0.0046	-0.017	0.045	0.025
	Ethanol from Wood	0	0.026	0.0021	0.045	0.074
	Biogas from Dung	0	0	0	0.16	0.16
	LPG	0.12	-0.0063	-1.7E-04	0.15	0.27

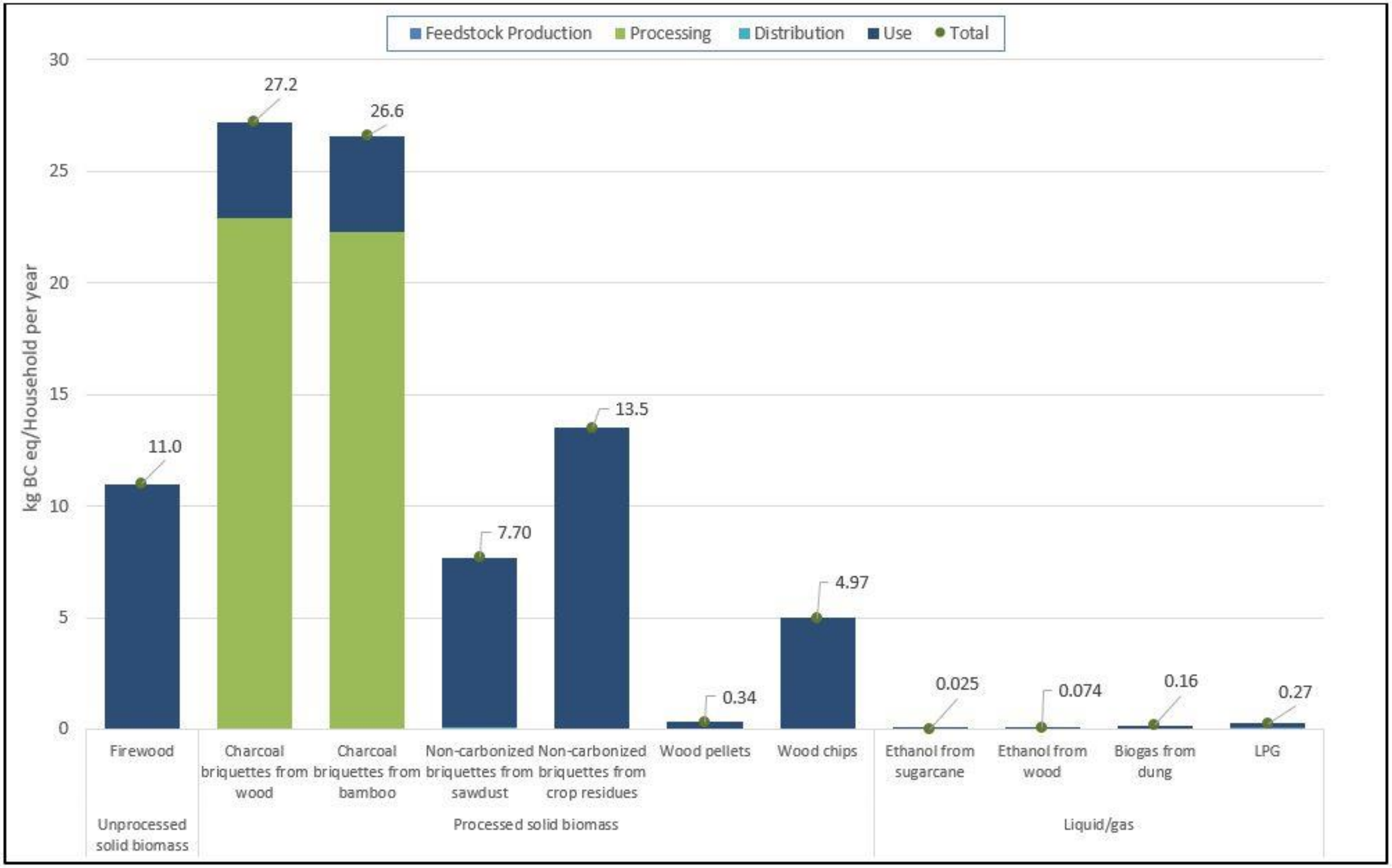


Figure A-53. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (Nigeria)
To produce, distribute and use cooking fuels by a single household per year

A.6.2.5 Particulate Matter Formation Potential

Table A-59 and Figure A-54 show the particulate matter formation impact results for fuels in Nigeria by life cycle stage. Particulate matter can contribute to many negative health impacts such as effects on breathing and respiratory systems, damage to lung tissue, cancer, and premature death. Primary and secondary pollutants leading to particulate matter formation as well as PM2.5 are characterized here to kg PM10 eq. Charcoal briquettes lead to the greatest particulate matter formation impacts, followed by briquettes from crop residues/sawdust and firewood. For charcoal briquettes, the carbonization of the wood in the kiln dominates the overall life cycle impacts. Charcoal briquettes from bamboo have slightly lower particulate matter impacts than wood charcoal briquettes. This is because a larger portion of bamboo charcoal briquettes are estimated to be produced in hot-tail kilns; whereas, all wood charcoal briquettes in Nigeria are assumed to be produced in traditional earth mound kilns. Advanced liquid fuels as well as biogas and wood pellets have comparably small particulate matter impacts.

Table A-59. Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (Nigeria)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	**Processing**	**Distribution**	**Use**	**Total**
Unprocessed Solid Biomass	Firewood	0	0	0	37.4	37.4
Processed Solid Biomass	Charcoal Briquettes from Wood	0	90.6	0.34	11.2	102
	Charcoal Briquettes from Bamboo	0	87.5	0.34	11.2	99.0
	Non-Carbonized Briquettes from Sawdust	0	3.25	0.34	26.0	29.6
	Non-Carbonized Briquettes from Crop Residues	0	0.0027	1.7E-04	63.0	63.1
	Wood Pellets	0	0.16	0.19	1.66	2.02
	Wood Chips	0	0.058	0.0055	17.0	17.0
Liquid/Gas	Ethanol from Sugarcane	0.51	0.025	0.22	0.0069	0.76
	Ethanol from Wood	0	0.98	0.055	0.0069	1.04
	Biogas from Dung	0	0	0	0.84	0.84
	LPG	1.02	0.10	0.0058	0.79	1.92

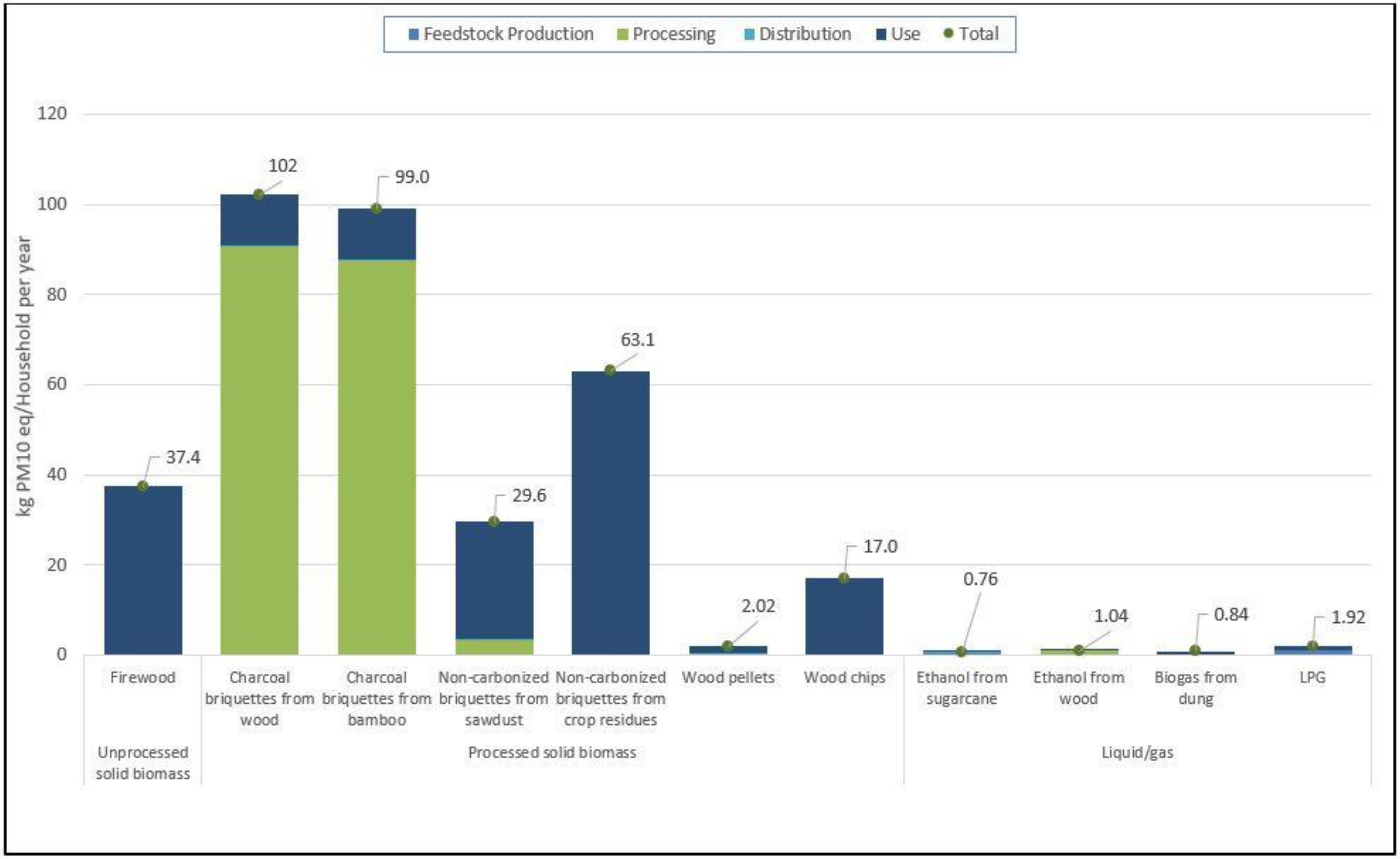


Figure A-54. Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (Nigeria)
To produce, distribute and use cooking fuels by a single household per year

A.6.2.6 Fossil Fuel Depletion

Table A-60 and Figure A-55 provide the fossil fuel depletion impact results for fuels in Nigeria by life cycle stage. Fossil depletion captures the consumption of fossil fuels, primarily coal, natural gas, and crude oil. All fuels are normalized to kg oil eq based on the heating value of the fossil fuel relative to the heating value of a kg of oil. The fossil depletion associated with firewood as well as biogas and ethanol from wood is negligible, as these fuels are not derived from fossil fuel, and collection of these fuels is done manually. While biomass fuels are not derived from fossil fuels, some fossil fuels may be consumed across the life cycle of these fuels for energy inputs to fuel production and processing, distribution, and disposal. Fossil depletion for wood pellets is associated with electricity usage for pelletization and some transport, while sugarcane ethanol fossil depletion is primarily from fertilizers during cane production, as well as diesel for farm operation and distribution of the feedstock and fuel. Some fossil depletion impacts are also seen for processing the wood chips and non-carbonized briquettes for the portions of these fuels that are not processed manually (as discussed in detail in Appendix B, 3% of non-carbonized and carbonized wood/bamboo briquetting is modeled as mechanized in Nigeria, and 28% of wood chipping is modeled as mechanized in Nigeria). Fossil depletion impacts are highest for LPG as this source of energy relies on fossil fuels.

Table A-60. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (Nigeria)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed solid biomass	Firewood	0	0	0	0.11	0.11
Processed solid biomass	Charcoal briquettes from wood	0	0.18	0.063	0.0064	0.25
	Charcoal briquettes from bamboo	0	0.12	0.063	0.0064	0.19
	Non-carbonized briquettes from sawdust	0	1.89	0.063	0.060	2.01
	Non-carbonized briquettes from crop residues	0	2.36	3.2E-05	0.042	2.41
	Wood pellets	0	128	0.036	0.0029	128
	Wood chips	0	4.55	0.0010	0.048	4.60
Liquid/gas	Ethanol from sugarcane	30.4	1.26	10.3	0	42.0
	Ethanol from wood	0	17.2	0.010	0	17.2
	Biogas from dung	0	0	0	0	0
	LPG	378	1,560	5.55	662	2,605

Figure A-55. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (Nigeria)
To produce, distribute and use cooking fuels by a single household per year

A.6.2.7 Water Depletion

Table A-61 and Figure A-56 illustrate the water depletion impact results for fuels in Nigeria by life cycle stage. Water depletion results are based on the volume of fresh water inputs over the life cycle of the assessed fuels. Water may be incorporated in the fuel product, evaporated, or returned to the same or different water body or to land. If the water is returned to the same water body, it is assumed the water is returned at a degraded quality, and therefore is considered consumptive use. Water consumption includes evaporative losses from establishment of hydroelectric dams but does not include the water passing through the turbine, since that water is not removed from its source. The hydropower in the electricity mix drives the overall water depletion impacts. Water depletion associated with wood pellets, the fuel with the highest water consumption impacts, is due to electricity usage during palletization (with 19.7% of the electricity grid mix in Nigeria from hydropower).[244] Electricity also drives the minimal water depletion impacts for the 3% of briquettes pressed with motorized machines in Nigeria. Water depletion impacts are also notable for sugarcane ethanol, as some irrigation is required for the cane production. Some water depletion impacts are also seen for the biogas to maintain the digester, but these are negligible when compared to the evaporative losses from hydropower in the electricity grid. Some water inputs are required for the production of LPG during crude oil extraction and petroleum refining. Water depletion impacts are negligible for the traditional biomass fuels (i.e. firewood), which are not irrigated. Because the water content of these fuels comes from the atmosphere as rainfall, the water released back to the atmosphere when the biomass is dried or combusted is not considered consumptive use.

Table A-61. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (Nigeria)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	0.82	0.82
Processed Solid Biomass	Charcoal Briquettes from Wood	0	1.18	6.0E-04	0.049	1.23
	Charcoal Briquettes from Bamboo	0	1.16	6.0E-04	0.049	1.21
	Non-Carbonized Briquettes from Sawdust	0	11.7	6.0E-04	0.45	12.1
	Non-Carbonized Briquettes from Crop Residues	0	14.7	3.0E-07	0.32	15.0
	Wood Pellets	0	789	3.4E-04	0.014	789
	Wood Chips	0	4.70	9.9E-06	0.37	5.08
Liquid/Gas	Ethanol from Sugarcane	250	6.04	6.06	0	262
	Ethanol from Wood	0	4.48	9.8E-05	0	4.48
	Biogas from Dung	0	51.5	0	0	51.5
	LPG	87.0	34.6	29.6	0	151

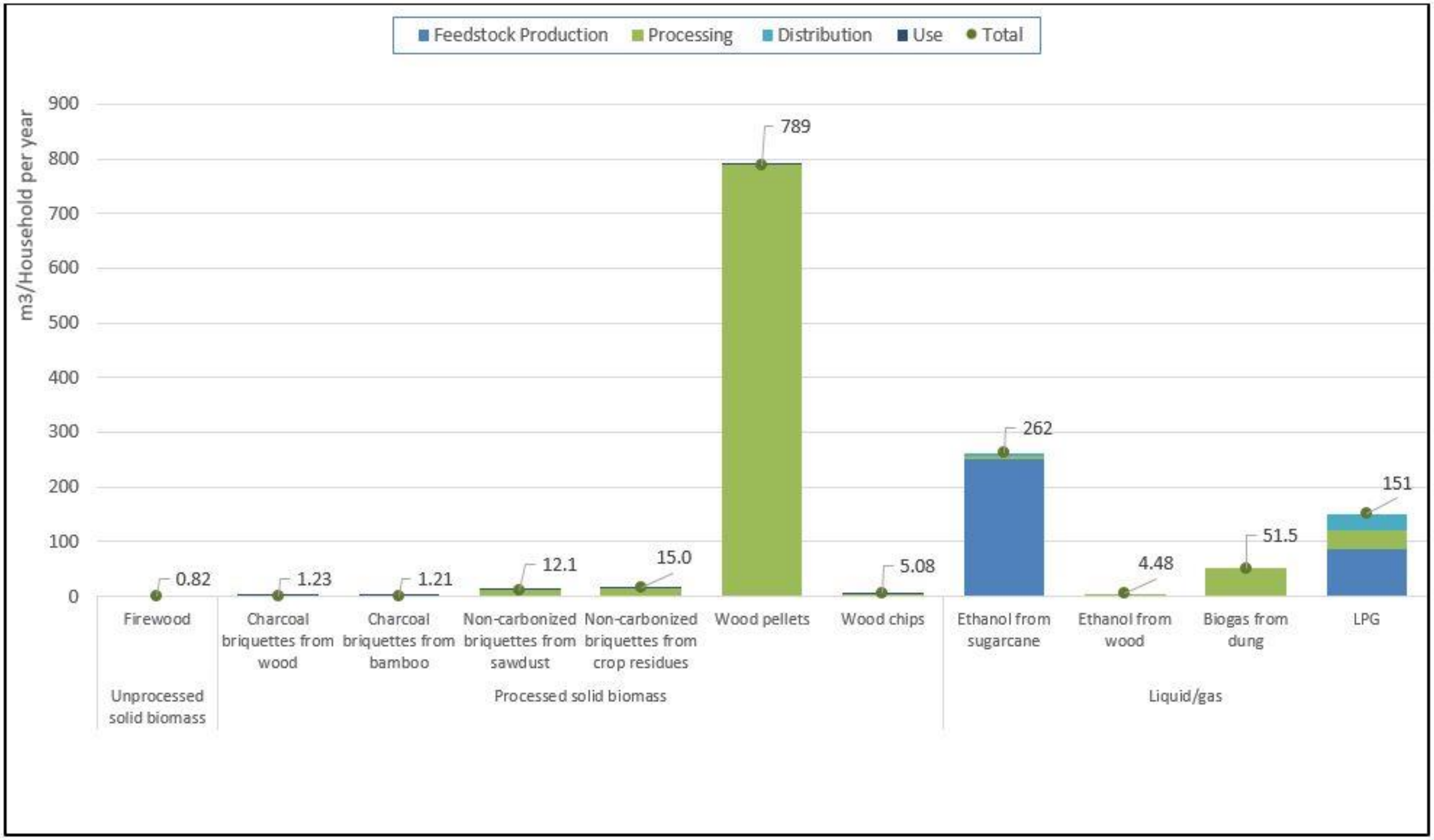


Figure A-56. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (Nigeria)

To produce, distribute and use cooking fuels by a single household per year

A.6.2.8 Terrestrial Acidification Potential

Table A-62 and Figure A-57 show the terrestrial acidification potential impact results for fuels in Nigeria by life cycle stage. Terrestrial acidification quantifies the acidifying effect of substances on their environment. Important contributing emissions include SO_2, NO_x, and NH_3. Ethanol contains no sulfur, so there are no sulfur dioxide emissions, a main cause of acidification, for the ethanol cookstove use stage. However, there are notable NOx emissions leading to acidification for the portion cane straw burned on the field. Firewood has the highest overall acidification impacts. The main contributing emissions leading to acidification potential for the traditional fuels are SO_x and NO_x. For instance, NO_x leads to 73% and SO_x leads to 27% of the firewood acidification impacts, respectively. Distribution acidification impacts in Nigeria are highest for transportation of the carbonized and non-carbonized briquettes since a greater mass of input fuel for the solid biomass is required to be transported a longer distance given the proximity of end users to forests in Nigeria (Appendix B provides detailed discussions of the model's transportation parameters). Distribution impacts are also notable for sugarcane ethanol, which is assumed to be transported via ocean freighter from Brazil, the world's largest producer of sugarcane ethanol.[327] The lowest overall acidification impacts are seen for biogas. Because land applied digested sludge from biogas production is used by another product system, it is considered to be outside the system boundaries for this analysis; however, it is possible that this land applied digested sludge could lead to emissions of ammonia, an acidifying substance.

Table A-62. Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (Nigeria)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	8.81	8.81
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.79	0.82	1.66	3.27
	Charcoal Briquettes from Bamboo	0	0.77	0.82	1.66	3.25
	Non-Carbonized Briquettes from Sawdust	0	0.057	0.82	6.13	7.01
	Non-Carbonized Briquettes from Crop Residues	0	0.0087	4.1E-04	3.44	3.45
	Wood Pellets	0	0.50	0.46	0.54	1.50
	Wood Chips	0	0.12	0.013	3.98	4.11
Liquid/Gas	Ethanol from Sugarcane	2.56	0.10	0.73	0	3.39
	Ethanol from Wood	0	1.17	0.13	0	1.30
	Biogas from Dung	0	0	0	0.25	0.25
	LPG	2.40	0.31	0.018	1.41	4.13

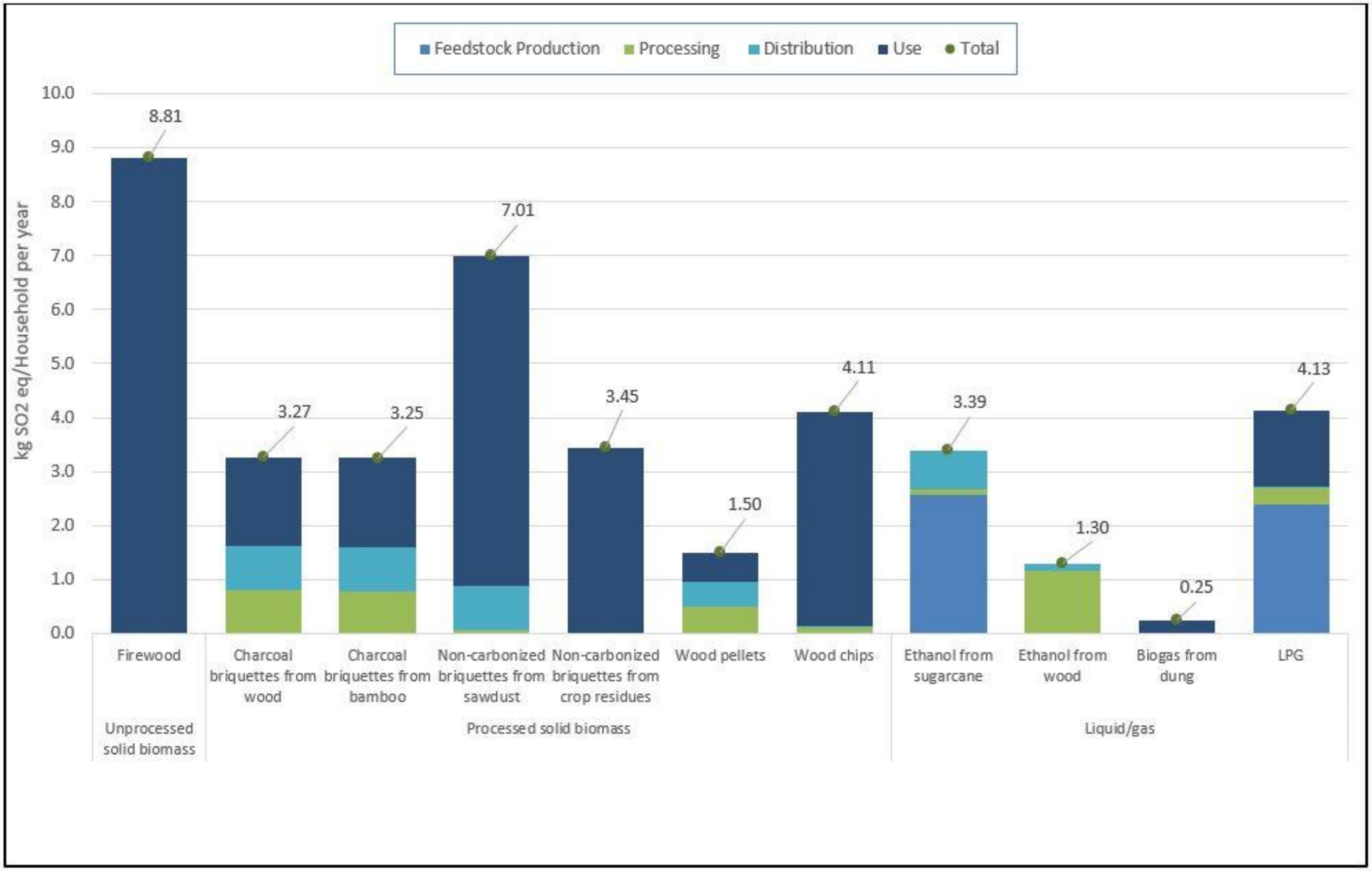


Figure A-57. Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (Nigeria)
To produce, distribute and use cooking fuels by a single household per year

A.6.2.9 Freshwater Eutrophication Potential

Table A-63 and Figure A-58 provide the freshwater eutrophication potential impact results for fuels in Nigeria by life cycle stage. Eutrophication assesses the impacts from excessive load of macro-nutrients to the environment and eventual deposition in freshwater, which can result in algal blooms, oxygen depletion, and fish kills. Pollutants contributing to this category are all P based (e.g. phosphate, phosphoric acid, phosphorus). Firewood results in the highest eutrophication potential impacts. This is due to the larger ash quantity produced from Firewood compared to all other fuels. The ash from the firewood, which contains phosphorus is assumed to be land applied, which leads to soil emissions and eventual runoff into freshwater. Ash production is also the reason other processed biomass fuels have a relatively high eutrophication impact. The non-carbonized processed biomass fuels have slightly lower eutrophication potential impacts than traditional unprocessed biomass fuels. Because processed biomass burns more efficiently than unprocessed biomass, less fuel must be burned, leading to an overall lower quantity of ash produced. While impacts are comparably smaller for ethanol, there are some eutrophication impacts occurring from use of phosphorus based fertilizer in sugarcane production. There are no eutrophication impacts associated with biogas. Application of the digested sludge from the biogas system would likely lead to some eutrophication impacts, but utilization of this useful co-product is outside the system boundaries of this study. The digested sludge impacts are allocated to the product system it serves (i.e. nutrients for crop production). Impacts from fossil based fuels and biomass pellets are minimal compared to the traditional fuels.

Table A-63. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (Nigeria)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	2.65	2.65
Processed Solid Biomass	Charcoal Briquettes from Wood	0	1.10	6.8E-07	0.16	1.26
	Charcoal Briquettes from Bamboo	0	1.07	6.8E-07	0.16	1.23
	Non-Carbonized Briquettes from Sawdust	0	0.012	6.8E-07	1.46	1.48
	Non-Carbonized Briquettes from Crop Residues	0	4.3E-05	3.5E-10	1.05	1.05
	Wood Pellets	0	0.0032	3.9E-07	0.046	0.049
	Wood Chips	0	6.8E-04	1.1E-08	1.20	1.20
Liquid/Gas	Ethanol from Sugarcane	0.13	8.0E-04	8.5E-04	1.7E-05	0.13
	Ethanol from Wood	0	3.5E-05	1.1E-07	1.7E-05	5.3E-05
	Biogas from Dung	0	0	0	0	0
	LPG	0.014	0.0047	1.6E-04	0	0.019

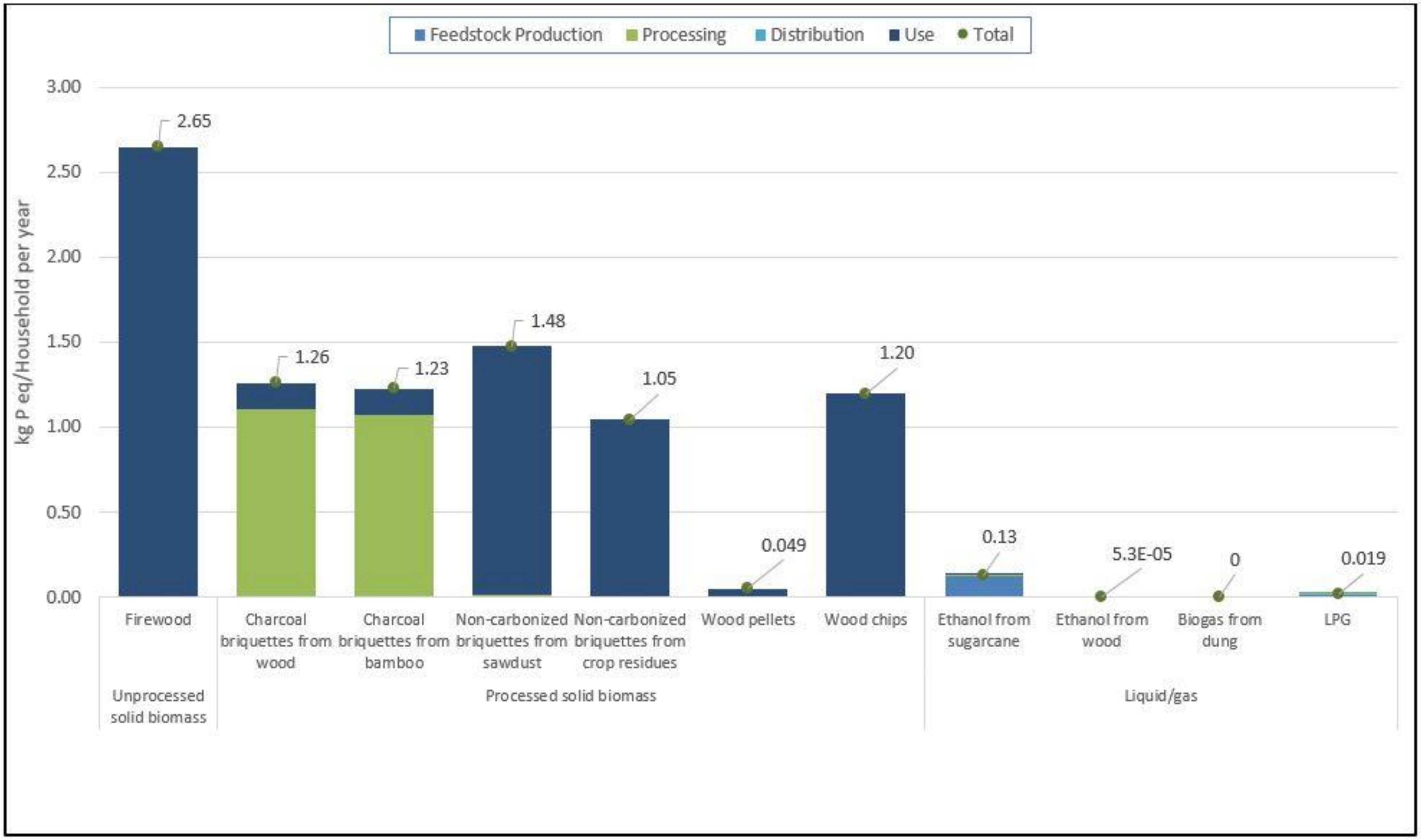


Figure A-58. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (Nigeria)
To produce, distribute and use cooking fuels by a single household per year

A.6.2.10 Photochemical Oxidant Formation Potential

Table A-64 and Figure A-59 present the photochemical oxidant formation potential impact results for fuels in Nigeria by life cycle stage. The photochemical oxidant formation (i.e. smog formation) results are an indicator of the potential for formation of reactive substances that cause harm to human health and vegetation. Results are characterized here to kg of non-methane volatile organic compounds (NMVOC) eq. Some key emissions for cookstove fuel systems that contribute to photochemical oxidant formation include carbon monoxide, methane, nitrogen oxides, NMVOCs, and sulfur dioxide. Firewood and charcoal briquettes lead to the greatest photochemical formation impacts, followed by processed biomass fuels. For charcoal briquettes, impacts are split between the fuel processing stage (carbonization in a kiln) and the use stage. Photochemical oxidant formation impacts are relatively small for the liquid fuels, processed non-carbonized biomass and biogas.

Table A-64. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (Nigeria)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	399	399
Processed Solid Biomass	Charcoal Briquettes from Wood	0	376	1.40	77.4	455
	Charcoal Briquettes from Bamboo	0	374	1.40	77.4	452
	Non-Carbonized Briquettes from Sawdust	0	2.25	1.40	276	280
	Non-Carbonized Briquettes from Crop Residues	0	0.012	7.0E-04	48.9	48.9
	Wood Pellets	0	1.49	2.1E-05	1.64	3.13
	Wood Chips	0	0.20	0.023	180	180
Liquid/Gas	Ethanol from Sugarcane	12.2	0.028	0.56	1.00	13.8
	Ethanol from Wood	0	2.03	0.23	1.00	3.25
	Biogas from Dung	0	0	0	1.31	1.31
	LPG	17.4	0.40	0.046	17.0	34.9

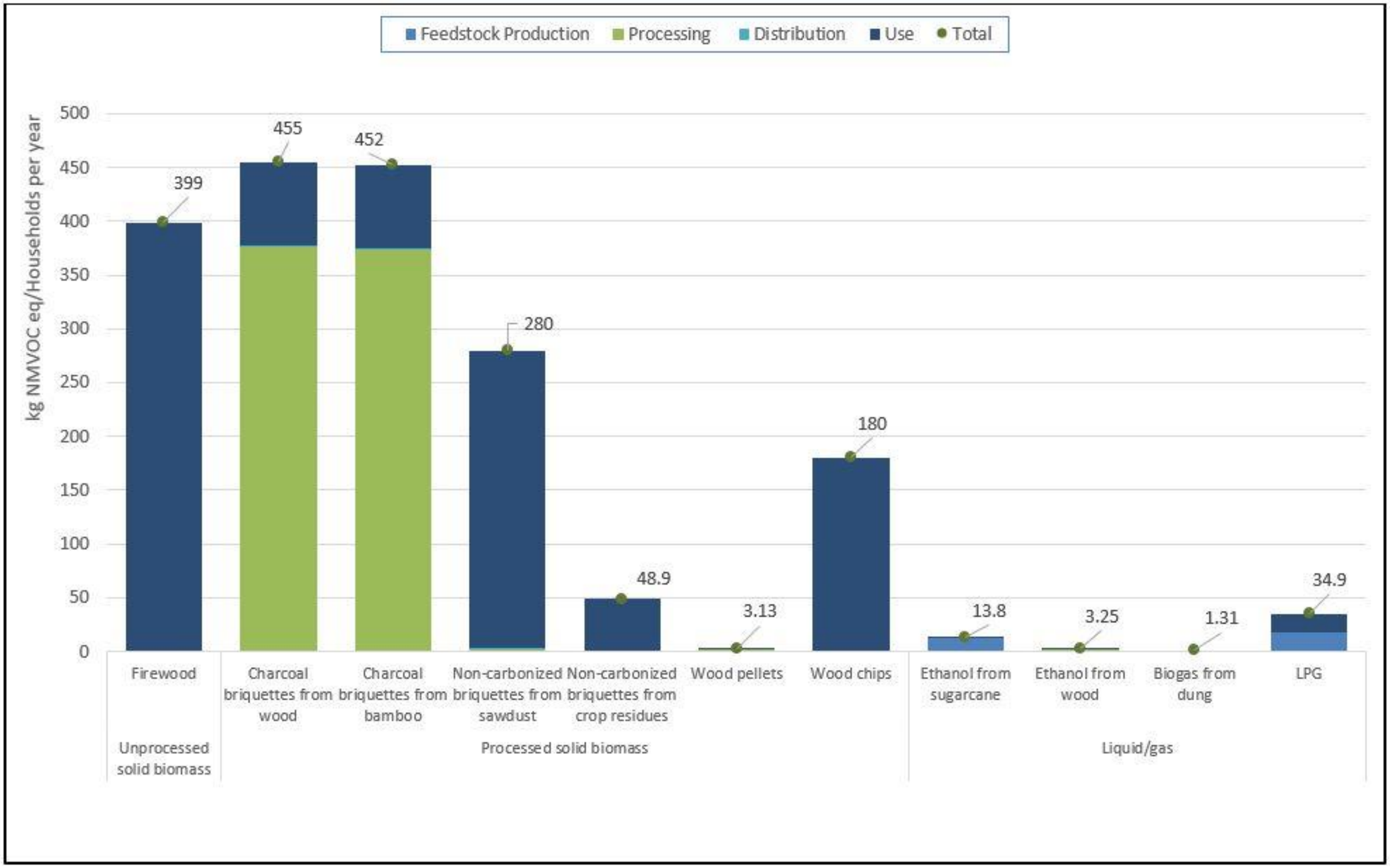


Figure A-59. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (Nigeria)

A.6.3 Economic Indicators for Nigeria

A.6.3.1 Fuel Use

Figure shows the percentages of the population in Nigeria using various types of fuel as their primary cooking fuel. Over 70 percent of the population use biomass fuel (primarily firewood) for cooking.[329,330,331,332] The remaining households primarily use kerosene, although small percentages of the population use LPG, coal, charcoal, electricity, dung, and other fuels.[333] Fuels such as ethanol, carbonized and non-carbonized wood briquettes, and biogas may be used on a very limited basis.[334]

As in other countries, fuel use patterns vary with the user's income level and whether they live in an urban or rural setting. Use of LPG is limited primarily to high income urban residents (a small percentage of the population), wood is used by the large numbers of low income rural residents, and a mix of wood, charcoal and kerosene is used by middle income residents in both urban and rural areas.[335] While individual user preferences vary, a survey of Nigerians found that kerosene was most commonly considered the most desirable fuel, primarily due to its ease of use.[336]

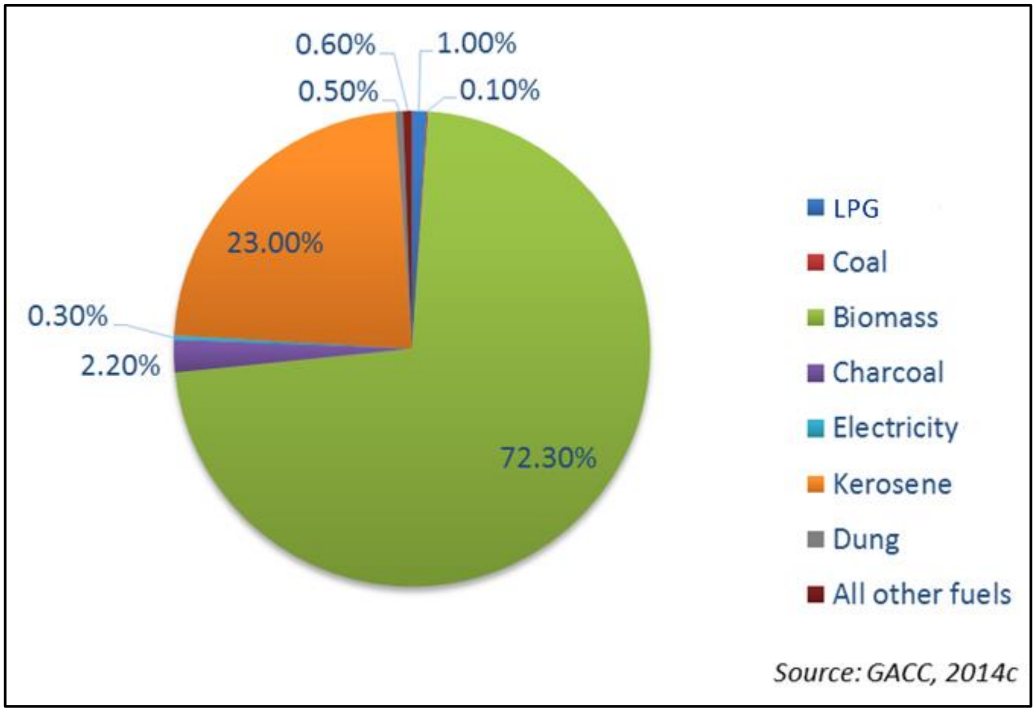


Figure A-60. Current Cooking Fuel Mix in Nigeria

A.6.3.2 Fuel Imports, Exports, Production, and Demand in Nigeria

Table shows the levels of imports, exports, production, and demand (assumed to be equal to current consumption) of several fuels in Nigeria. The data on total and household consumption do not differentiate between fuel use for cooking and fuel use for other purposes such as heating. LPG is not widely used, with 129,000 tonnes produced each year and only 17,000 tonnes consumed by households.[337] Nigeria produces about 12,000 tonnes of ethanol and consumes about 14,000 tonnes,[338] but ethanol was not reported as being widely used as a cooking fuel, so the consumption is likely for transportation or other purposes. Nigeria is estimated to produce about 64.3 million tonnes of firewood per year,[339] and over 70 percent of the population uses firewood for cooking,[340,341,342,343] but data on the amounts of firewood consumed, in total or by households, are not available. Forest land in Nigeria has been decreasing rapidly within recent years, with sources citing rates of decrease ranging from 4[344] to 11[345] percent per year, so households will likely need to find alternative fuels to supply some or all of their cooking needs. After firewood, kerosene and charcoal are the most widely used fuels in Nigeria.[346,347,348] The country produces 1.2 million tonnes of charcoal, which are all consumed by households.[349] While trade figures are not available for these fuels in Nigeria, cooking fuels are not commonly imported.[350]

Table A-65. Fuel Imports, Exports, Production, and Demand in Nigeria (Tonnes per Year)

Fuel	Imports	Exports	Production	Consumption		Sources
				Total	Household	
LPG	No data	No data	129,000	107,000	17,000	UNSD, 2011
Ethanol	No data	No data	11,297	13,966	No data	OECD/FAO, 2014
Firewood	No data	No data	64,413,551	No data	No data	FAO, 2014
Charcoal Briquettes	No data	No data	1,171,000	1,171,000	1,171,000	UNSD, 2011

A.6.3.3 Fuel Cost in Nigeria

Figure shows the price per household per year for the cooking fuels in Nigeria for which cost data are available. Purchased firewood is the most expensive fuel, at $289 per household per year. Persons in rural areas are typically able to collect firewood at no cost, while those in urban areas must purchase it.[351] LPG and wood charcoal are similar in cost, between $140 and $160 per household per year.[352,353] Wood and charcoal have the advantage of being available in relatively small quantities, which make it more affordable for poorer household compared to LPG, which must generally be purchased in large cylinders. Although kerosene is not in the scope of this analysis, it is worth noting that kerosene costs roughly half as much as purchased wood,[354] but this is in part due to kerosene subsidies for urban users.[355]

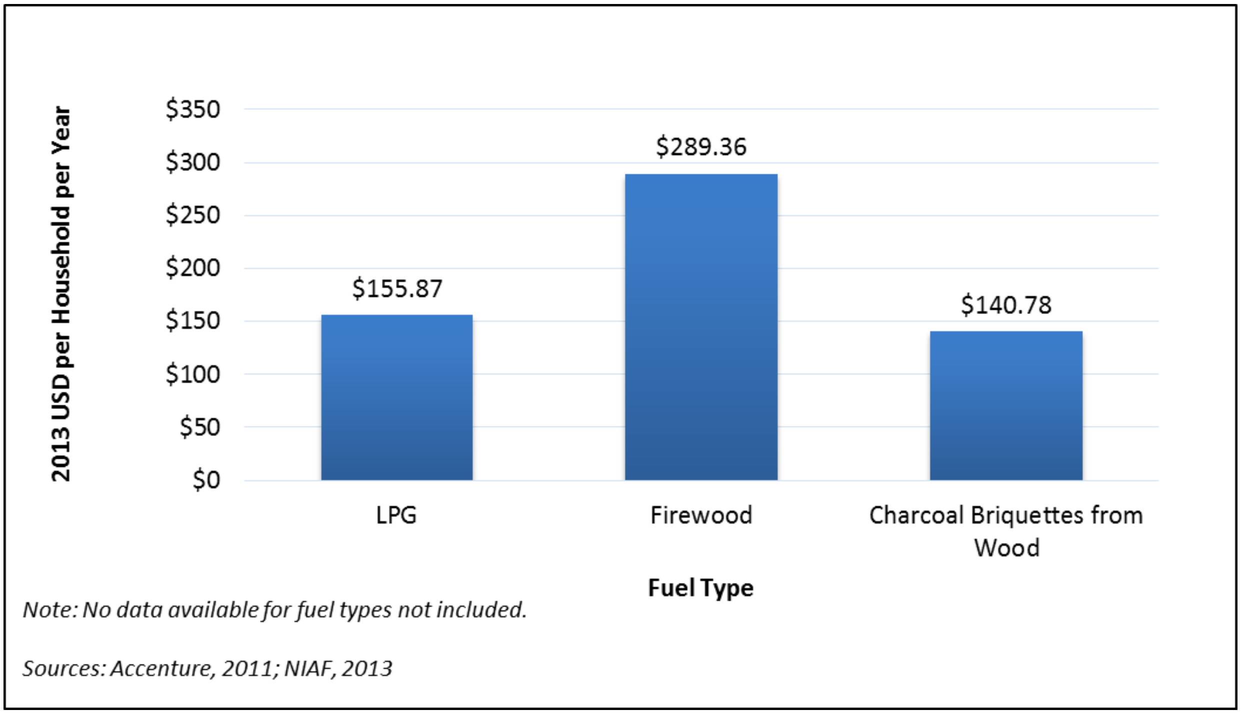


Figure A-61. Fuel Cost Indicator for Cooking Fuels in Nigeria

A.6.4 Social Indicators for Nigeria

A.6.4.1 Government Policies/Programs

Key drivers of government action in Nigeria's energy sector appear related to environmental and public health issues, and impacts will most likely be felt among those formally and informally involved in wood-based fuel production and use. Dating back to Nigeria's 2003 National Energy Policy, which sought to improve efficiency in the use of firewood and simultaneously promote alternatives, the government has been engaged with regulating traditional biomass fuels. The Ministry of Environment endorsed participation in a REDD+ (the UN-led program for Reducing Emissions from Deforestation and Forest Degradation) readiness program in 2011, and policies at both the national- and state-level have been introduced to raise awareness about the public health impacts of indoor air pollution and firewood combustion.[356]

The government has reinforced these efforts indirectly by promoting firewood alternatives. Nigeria has an ongoing kerosene subsidy (though the industry might undergo privatization due to supply and price fluctuations)[357] and the government, despite mixed results, has maintained substantial involvement in the LPG sector. Nigeria's Department of Petroleum Resources (DPR) is the principal regulator of the LPG industry[358] and is in charge of granting the licenses required to do business as LPG retailers and suppliers/marketers.[359] The DPR is criticized for its weak legal framework,[360] which has led to issues such as the loss of control of cylinders and the management of refilling practices and inconsistent license approvals.[361] Separate from the DPR is the Standards Organization of Nigeria (SON), which produces safety standards for LPG cylinders, valves, and regulators. As of 2004, the SON was involved in an awareness campaign to promote cylinder safety among end-users. Specifically, the program seeks to improve vigilance among LPG users so defective cylinders can be removed from circulation before they reach the point of failing a mandatory inspection.[362]

Complementing Nigeria's LPG regulations are fuel-neutral policies with implications for the energy sector. These include commitments among state governments throughout Nigeria to fund road repairs,[363] which has the potential to improve LPG distribution networks and improve access to filling stations among rural communities, and the Ministry of Environment's renewable energy fund, which promotes clean cookstove adoption by providing rebates on qualifying technology. Relatedly, carbon financing (through Clean Development Mechanism credits) is used to improve clean cookstove uptake, though key challenges remain: persistent cost barriers, the stoves are not appropriate to all regions, and stringent monitoring requirements make implementation difficult.[364] While not specific to the energy sector, one promising initiative is the Ministry of Women Affairs partnership with the Bank of Industry (BOI) to provide microfinance options for women interested in expanding their businesses.[365] This has the potential to help women participating in the clean cooking sector scale their operations and compete with entities benefitting from traditional financing mechanisms.

A.6.4.2 Supply & Access Challenges

Reliability data are only available for wood-based fuels and LPG. Although charcoal has traditionally had a very reliable supply chain (relative to electricity supply),[366] Nigeria's forests have been decreasing at a rate of 3 percent per year over recent years[367] – one of the highest rates in the world.[368] This has substantial implications for both the charcoal industry and those relying on manually-gathered wood. Approximately 8.2 million rural Nigerian households (28 percent of total households) rely on collected firewood and represent the segment of the population most vulnerable to unsustainable forestry practices. Also implicated are the 6.6 million rural households (22 percent of the total) and the 13.2 million urban households (44 percent of the total), who rely on a mix of firewood and other fuels such as charcoal and kerosene.[369]

Although Nigeria's LPG sector faces regulatory challenges (see A.6.4.1 above), reliability proper is not considered an issue as the country produces 129,000 tonnes of LPG per year, 17,000 of which is consumed in Nigerian households.[370]

A.6.4.3 Distribution & Adoption Challenges

Although there has been market penetration by some of the alternative fuels in Nigeria—LPG is fully commercialized, biogas producers are involved in advanced pilot projects,[371] there has been some wood-based charcoal uptake[372]—challenges facing the distribution and use of the fuels, with the exception of LPG, remain broad in scope. For example, many people lack awareness of the health benefits and energy savings associated with nontraditional fuels.[373] A more subjective barrier to the adoption of nontraditional fuels is the cultural attitude that certain dishes taste better when cooked over wood.[374] Relatedly, there is a strong tradition in Nigeria of hosting large social gatherings (50+ attendees) around two times a month, and firewood is the fuel of choice when cooking for these events. Given the large volume of cooking required, "even LPG households resort to fuelwood,"[375] illustrating the impact tradition can have on cooking fuel choice even among those adopting newer methods.

In addition to these general observations, several specific insights were available with respect to LPG in Nigeria. The insights can be organized into four primary challenges related to the distribution and use of LPG: (1) import facilities at the port of Lagos are bottlenecked,[376,377] (2) distribution capacity is underutilized with 85 percent of filling plants closed,[378] (3) transport consistency is hampered by poorly maintained trucks[379] and roads,[380] and (4) the cylinder population is in poor condition, suffering from a lack of proper maintenance and licensing procedures.[381] Despite these challenges, the broad—however underutilized—reach of the country's distribution infrastructure suggests that targeted solutions might lead to more reliable delivery in the future.[382] The perception that LPG is a "rich man's cooking fuel" and, therefore not considered as an alternative by many people,[383] would still potentially need to be addressed before wide-scale adoption is possible.

A.6.4.4 Protection & Safety

The only fuel-specific safety concerns for which data are available in Nigeria relate to the purchase and use of LPG. Two-thirds of respondents to a survey conducted in Lagos stated that LPG is dangerous and, some respondents stated that children were allowed to light kerosene stoves, but not even touch LPG stoves. Moreover, in Maiduguri, perceived danger was the second-most frequently cited reason for not using LPG, second only to cost, and well ahead of supply uncertainty and the hassle of obtaining refills.[384] Alternatively, respondents in Owerri stated they experienced hostile encounters at retail outlets, though details of specific incidents were not provided.[385] A 2011 market assessment indicates that safety concerns might not be based solely on prejudice or perceived danger; rather, it found that LPG leakages and adulteration are common, thus substantiating the previously mentioned concerns.[386]

The informal collection of crop and forest residues (twigs, branches, and so forth) usually occurs somewhat close to the household, and no safety issues were found in the literature. Although certain risks such as animal encounters, accidents occurring during the manual transport of firewood, and an increased likelihood of gender-based violence are assumed to be present when fuel is gathered in remote locations, no fuel-specific data were found for Nigeria.

A.6.4.5 Time & Drudgery

Nigerian households spend an average of 1.7 hours per day gathering firewood,[387] with one-way fuel collection trips taking between 25 and 65 minutes depending on the proximity of forests and agricultural lands.[388] Although limited data are available regarding comparative time savings with alternative fuels, one study in Lagos found that time spent purchasing LPG ranged between 10 minutes for urban users with middle-class incomes and 31 minutes for the rural poor.[389] This represents a substantial improvement over the time spent gathering traditional cookfuel.

A.6.4.6 Income Earning Opportunities

Given the newness of the feedstock-fuel combinations in the present study, limited information regarding the income earning opportunities associated with specific cookfuels is available. One cookfuel for which some insights are available is LPG. According to the UN Statistics Division's 2011 database, Nigeria produced 129,000 tonnes of LPG, but almost the entire supply (all but 17,000 tonnes) were exported.[390] Traditionally, LPG that is consumed domestically is distributed through highly-fragmented markets, making it difficult to develop enterprise-level data.[391] Despite these challenges, the informality of Nigeria's LPG sector indicates a lack of structural barriers to market entry for new enterprises, and the large share of exports suggests that the LPG supply would be readily available should local domestic consumption increase.[392]

Another fuel that has an opportunity for growth in Nigeria is ethanol. For example, the success of Project Gaia, a producer of ethanol from cassava agricultural residue and cashew apple, demonstrates the market potential for fuel products that are efficient—one liter of ethanol replaces 16 pounds of wood—and addresses the safety concerns that can stand in the way of new fuel adoption. For example, project Gaia's ethanol is packaged in canisters that are leak-proof and depressurized, and the accompanying stove is designed so that the heat source must be extinguished before the fuel canister can be refilled.[393]

A.6.4.7 Opportunities for Women Along the Value Chain

According to the Global Alliance for Clean Cookstoves 2013 Results Report, the clean cookstove industry in Nigeria currently has 78 employees (31 percent of whom are women) and 219 microentrepreneurs (77 percent of whom are women).[394] However, there are currently no data available to estimate potential increases of skills for women with respect to specific fuels. Evidence from Solar Sister, a clean cookstove enterprise, suggests that developing business and planning skills for women as part of the entrepreneurial process can prove successful in Nigeria.[395]

A.7 Detailed Results for Ghana

A.7.1 Overview of Ghana

Ghana is Western Africa's second most populous country, with the population evenly divided between urban and rural areas. [396] Almost 30 percent of the people live below the international poverty line of $1.25 per capita per day.[397,398] About half of Ghana's population relies on biomass (primarily firewood).

Adequate supply of fuel to sustainably support current or increasing levels of use is an important concern, particularly for biomass fuels. Ghana has shown an overall trend of an approximately 2 percent decrease in forest land per year over recent years.[399] Seventy-two percent of the country is vulnerable to desertification,[400] and recurrent drought in the north severely affects agricultural activities.

Finally, cultural issues around food and cooking fires are an important consideration. The flavor imparted to certain foods by specific cooking fuels can be very important to consumers, leading to resistance to changing fuel types. Households across Ghana generally eat similar foods and have the same cooking habits; the primary difference is fuel choice. In northern Ghana and rural areas, basic wood stoves, such as three-stone stoves and mud stoves, are most common.[401] Many households have multiple stoves, cooking outdoors with firewood and indoors with cleaner fuels; different fuels may be used for different types of meals.[402]

The following sub-sections address the environmental, economic, and social considerations related to cooking fuels and stoves for Ghana in greater detail.

A.7.2 Environmental Indicators for Ghana

This section covers the detailed Ghana LCA results for the ten environmental indicators assessed for each fuel. The stove thermal efficiency by fuel and the fuel heating values employed in this study to calculate the LCA results are provided in Table A-66 and Table A-67, respectively. The remainder of this section presents results for each environmental indicator.

Table A-66. Stove Thermal Efficiency Applied by Fuel for Ghana

Fuel Type	Stove Thermal Efficiency	Sources
Firewood	14.0%	Afrane & Ntiamoah, 2012
Charcoal Briquettes from Wood	18.0%	Afrane & Ntiamoah, 2011
Charcoal Briquettes from Bamboo	18.0%	Afrane & Ntiamoah, 2011
Non-Carbonized Briquettes from Sawdust	20.33%	GACC, 2015a Urban Uganda, 2015
Non-Carbonized Briquettes from Crop Residues	31.0%	GACC, 2015a
Wood Pellets	53.0%	Jetter et al., 2012
Wood Chips	31.0%	GACC, 2015a
Ethanol from Sugarcane	53.0%	Aprovecho Research Center, 2009
Ethanol from Wood	53.0%	Aprovecho Research Center, 2009
Biogas from Dung	55.0%	Afrane & Ntiamoah, 2011
LPG	57.0%	Afrane & Ntiamoah, 2011

Table A-67. Fuel Heating Values for Ghana

Fuel Type	HHV (MJ/kg)	Sources
Firewood	14.0	Afrane & Ntiamoah, 2012
Charcoal Briquettes from Wood	25.72	Afrane & Ntiamoah, 2011
Charcoal Briquettes from Bamboo	25.72	Afrane & Ntiamoah, 2011
Non-Carbonized Briquettes from Sawdust	18.8	Davies et al., 2013 Ferguson, 2012
Non-Carbonized Briquettes from Crop Residues	15.6	FAO, 2015 Duku et al., 2011
Wood Pellets	17.94	Singh et al., 2014 Jetter et al., 2012
Wood Chips	14.0	Boy et al., 2000
Ethanol from Sugarcane	28.3	Aprovecho Research Center, 2009
Ethanol from Wood	28.3	Aprovecho Research Center, 2009
Biogas from Dung	17.71	Afrane & Ntiamoah, 2011
LPG	45.84	Afrane & Ntiamoah, 2011

A.7.2.1 Total Energy Demand

Table A-68 and Figure A-62 display the total energy demand impact results for fuels in Ghana by life cycle stage. Total energy demand sources consist of non-renewable fuels (natural gas, petroleum, coal, and nuclear) and "renewable" fuels (e.g. biomass, hydro). Energy demand tracks all energy inputs across the life cycle of the fuel, with energy impacts shown at the point of use of the relevant fuel.

The total energy demand results are largely a function of the fuel heating value and thermal efficiency of the fuel and stove combination (Table A-67 and Table A-66). Stoves with higher efficiencies (e.g., LPG, biogas, ethanol, and biomass pellets) have a lower total energy demand overall, because more of the heating value of the fuel is converted into useful cooking energy and therefore less fuel must be produced, transported, and burned to deliver the same amount of cooking energy.

A number of observations can be made regarding energy results for the various types of fuels. For sugarcane ethanol, the feedstock energy results include not only the energy value of the sugar that is converted to ethanol but also the energy content of the bagasse, which provides the majority of energy used to process the sugarcane to ethanol. A co-benefit of ethanol production is the production of electricity, which may be exported. As discussed in the Appendix B methodology, this model employs the cut-off allocation methodology; therefore, a credit is not given here to the sugarcane or wood ethanol for exported electricity, so the energy demand impacts for ethanol should be considered as the upper bounds for these fuel types.

For wood fuels, the wood pellets and wood chips have a lower total energy demand than traditional firewood. Wood chips and wood pellets typically have a lower moisture content, greater energy content, and greater surface area than the traditional solid biomass, which allows the fuel to combust more efficiently. It is also more common to see improved cookstoves, which have higher stove thermal efficiencies, used in combination with the wood chips and wood pellets in Ghana.

For briquettes, the energy demand impact for the carbonized briquettes from wood and bamboo is relatively higher compared to other fuels due to the lower stove efficiencies for metal charcoal briquette stoves in Ghana and the charcoal kiln energy impacts. That is, additional energy is consumed when burning firewood at the kiln to produce charcoal prior to charcoal briquette utilization in a cookstove. Similarly, in processing the commercially made non-carbonized sawdust briquettes (3% of sawdust briquettes are assumed to be produced commercially in Ghana), sawdust is combusted to remove the moisture content of the briquettes, which contributes to the relatively higher total energy demand of the sawdust briquettes compared to other non-carbonized processed biomass fuels. The remaining 97% of sawdust briquettes are modeled as pressed manually and dried naturally to 10% moisture content. This requires 1.5 kg wood input to each 1 kg briquette, assuming a 40% moisture content of the original greenwood.[173]

Overall, liquid and gas fuels as well as processed solid biomass fuels not requiring additional combustion of solid fuel for processing (e.g., wood pellets) lead to the lowest overall total energy demand impacts.

Table A-68. Total Energy Demand Potential Impacts for Cooking Fuel Types (Ghana)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	**Processing**	**Distribution**	**Use**	**Total**
Unprocessed solid biomass	Firewood	0	0	0	35,444	35,444
Processed solid biomass	Charcoal briquettes from wood	0	71,873	0.053	27,578	99,451
	Charcoal briquettes from bamboo	0	69,346	0.053	27,578	96,924
	Non-carbonized briquettes from sawdust	0	13,239	0.053	24,417	37,657
	Non-carbonized briquettes from crop residues	0	25.4	4.1E-04	15,872	15,898
	Wood pellets	0	3,382	0.69	9,366	12,749
	Wood chips	0	140	0.013	16,013	16,153
Liquid/gas	Ethanol from sugarcane	406	3,645	114	9,366	13,532
	Ethanol from wood	0	1,151	0.20	9,366	10,517
	Biogas from dung	0	0	0	8,790	8,790
	LPG	4,452	21,033	51.2	8,709	34,245

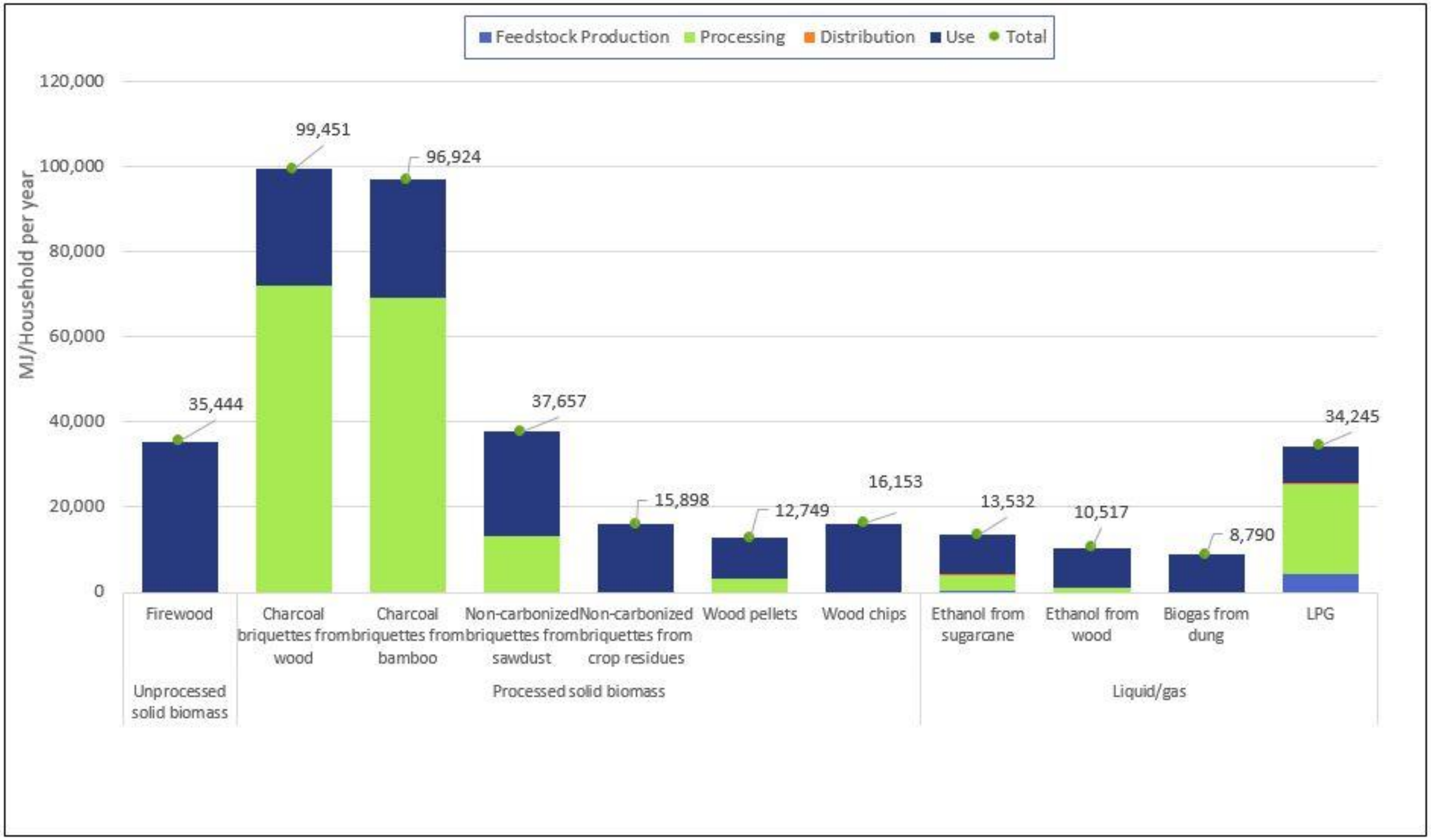


Figure A-62. Total Energy Demand (MJ) for Cooking Fuel Types (Ghana)
To produce, distribute and use cooking fuels by a single household per year

A.7.2.2 Net Energy Demand

Table A-69 and Figure A-63 illustrate the net energy demand impact results for fuels in Ghana by life cycle stage. Net energy demand is calculated in the same way as total energy demand, with the final energy delivered to the cooking pot deducted from the results. The net energy indicator is, therefore, the additional energy required for the life cycle of the cookstove fuel beyond what is delivered to the consumer for cooking purposes. For Ghana, 13.6 MJ of cooking energy are consumed per household per day, which equates to 4,964 MJ per household per year.[403, 404] Utilization of unprocessed solid biomass consumes seven times more energy than is provided to the pot, as listed in the last column of Table A-69. Similar levels of net energy demand are seen for non-carbonized briquettes from sawdust, and LPG. The lowest overall net energy demand is calculated for non-carbonized briquettes from crop residues, wood pellets, wood chips, ethanol, and biogas from dung. Production, processing, distribution, and use of these less energy intensive fuels uses 0.77 to 2.25 times the amount of energy delivered to the pot. Charcoal briquettes result in the highest net energy demand due to the lower yield at the kilns in African countries as compared to countries investigated in other world regions. For Ghana, 4.9 kg of wood are required for 1 kg charcoal output at the earth mound kiln.[405] Energy impacts are also higher for petroleum refining in Africa as compared to other world regions modeled, resulting in the notable net energy demand burdens of LPG.[327]

Table A-69. Net Energy Demand (MJ) for Cooking Fuel Types (Ghana)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total	Net Energy Consumed: Delivered Energy
		Feedstock Production	Processing	Distribution	Use		
Unprocessed solid biomass	Firewood	0	0	0	30,480	30,480	6.14
Processed solid biomass	Charcoal briquettes from wood	0	71,873	0.053	22,614	94,487	19.0
	Charcoal briquettes from bamboo	0	69,346	0.053	22,614	91,960	18.5
	Non-carbonized briquettes from sawdust	0	13,239	0.053	19,453	32,693	6.59
	Non-carbonized briquettes from crop residues	0	25.4	4.1E-04	10,908	10,934	2.20
	Wood pellets	0	3,382	0.69	4,402	7,785	1.57
	Wood chips	0	140	0.013	11,049	11,189	2.25
Liquid/gas	Ethanol from sugarcane	406	3,645	114	4,402	8,568	1.73
	Ethanol from wood	0	1,151	0.20	4,402	5,553	1.12
	Biogas from dung	0	0	0	3,826	3,826	0.77
	LPG	4,452	21,033	51.2	3,745	29,281	5.90

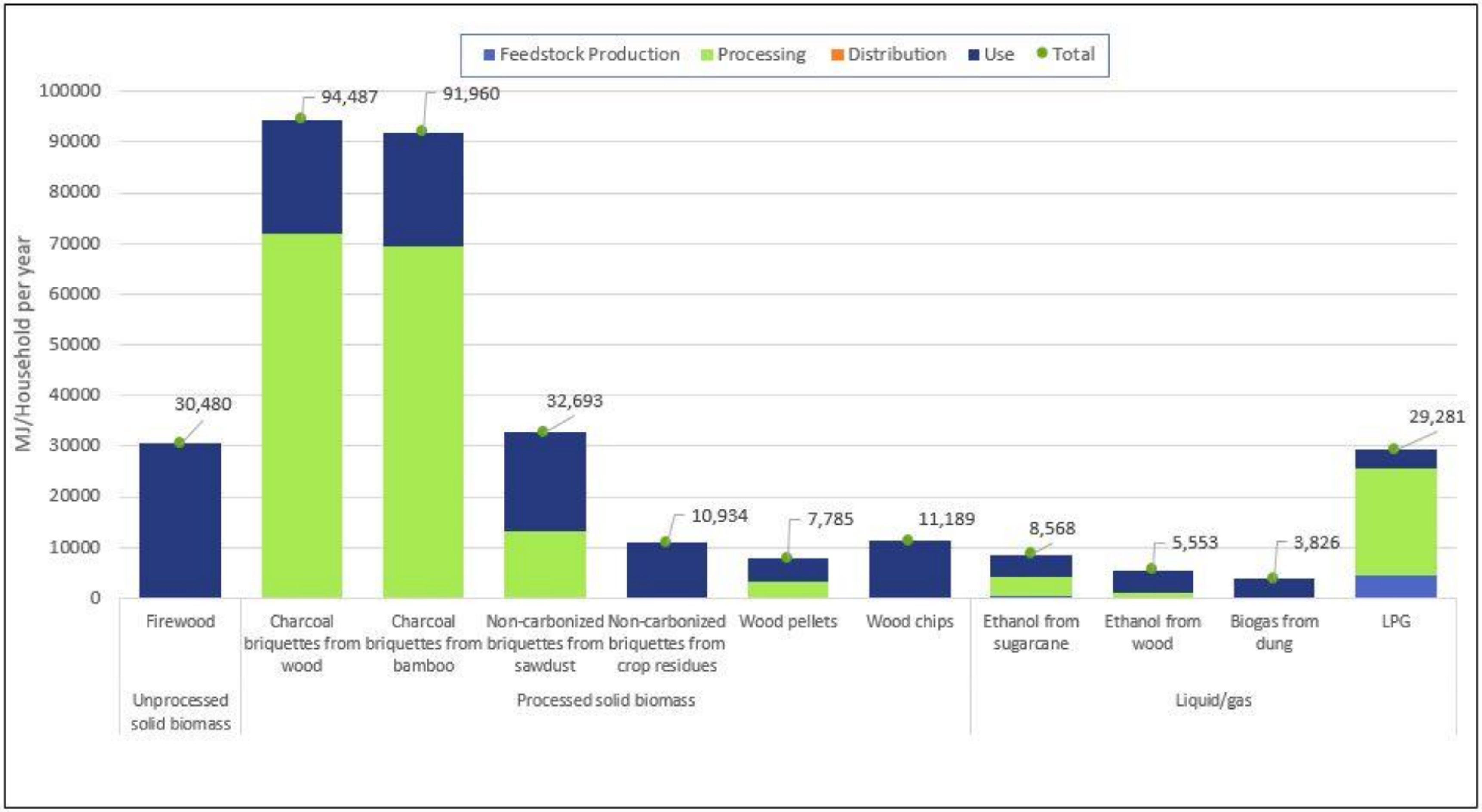


Figure A-63. Net Energy Demand (MJ) for Cooking Fuel Types (Ghana)
To produce, distribute and use cooking fuels by a single household per year

A.7.2.3 Global Climate Change Potential (100a)

Table A-70 and Figure A-64 present the GCCP impact results for fuels in Ghana by life cycle stage. The GCCP impact category represents the heat trapping capacity of greenhouse gases over a 100 year time horizon. Fossil fuel GCCP impacts are dominated by combustion emissions in the cookstove use stage.

Biogas GCCP impacts are primarily from methane leakage during the production of biogas in an anaerobic digester (1% of biogas escapes as fugitive emissions at the digester).[406] Sugarcane ethanol, crop residue briquettes, and charcoal briquettes from bamboo are derived from renewable biomass that removed CO_2 from the atmosphere during growth; therefore, the CO_2 emissions released from combustion of these fuels is considered carbon neutral, as discussed in detail in the Appendix B methodology. Impacts for these renewable fuels during the use phase are driven by nitrous oxide and methane emissions during cookstove use. Impacts associated with fertilizer production and emissions from application also play a role in the sugarcane ethanol overall impacts.

Based on the decreasing trend in forest area in Ghana, all of the wood harvested for use as cooking fuel is considered unsustainably sourced, and the combustion emissions for the non-sustainable use of wood are not considered carbon-neutral. This adjustment is also applied to other wood fuels (wood-derived charcoal briquettes, wood pellets and wood chips), but not to fuels derived from wood wastes (wood ethanol and non-carbonized briquettes from sawdust). With the cut-off modeling methodology used in this analysis, wood wastes are treated as a “free” product (all burdens are allocated to the primary wood product, e.g., lumber, which is outside the scope of this study), so emissions of biomass CO_2 for fuels derived from wood waste are treated as carbon neutral. For charcoal briquettes, GCCP impacts for carbonization of the wood in the kiln are higher in magnitude than the emissions from combustion of the charcoal briquettes in a cookstove. Charcoal kiln impacts are largely driven by the methane emissions during the carbonization process. Combustion emissions for bamboo-derived charcoal briquettes are lower than for wood-derived charcoal briquettes because bamboo is a renewable crop and all combustion emissions are considered carbon-neutral, while none of the wood combustion emissions are considered carbon-neutral, since the wood supply in Ghana is considered non-renewable based on the decreasing forest area. All GHGs associated with the production and combustion of LPG, including CO_2 emissions from cooking, are considered fossil-derived and accounted for in the GCCP impacts.

Table A-70. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (Ghana)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	3,990	3,990
Processed Solid Biomass	Charcoal Briquettes from Wood	0	4,618	91.2	2,886	7,595
	Charcoal Briquettes from Bamboo	0	1,005	91.2	440	1,536
	Non-Carbonized Briquettes from Sawdust	0	3.64	91.2	375	470
	Non-Carbonized Briquettes from Crop Residues	0	1.21	0.030	225	226
	Wood Pellets	0	73.6	51.1	1,702	1,826
	Wood Chips	0	4.70	0.99	1,800	1,805
Liquid/Gas	Ethanol from Sugarcane	56.7	3.22	8.18	4.75	72.9
	Ethanol from Wood	0	24.4	14.6	4.75	43.7
	Biogas from Dung	0	2.02	0	12.8	14.8
	LPG	523	4.15	2.44	1,385	1,915

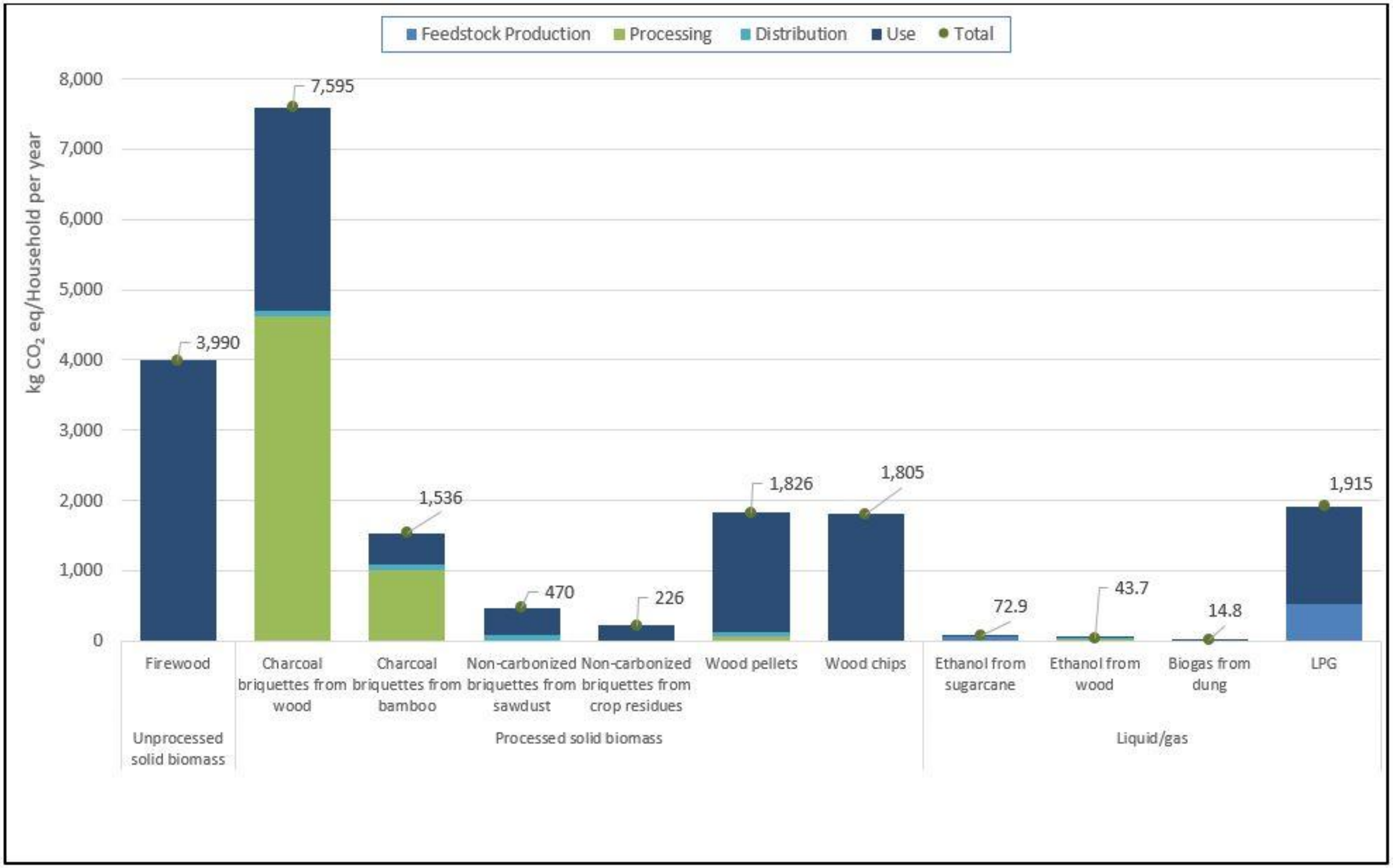


Figure A-64. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (Ghana)
To produce, distribute and use cooking fuels by a single household per year

A.7.2.4 Black Carbon and Short-Lived Climate Pollutants

Table A-71 and Figure A-65 display the black carbon and short-lived climate pollutants impact results for fuels in Ghana by life cycle stage. Black carbon (BC) is formed by incomplete combustion of fossil and bio-based fuels. BC is the carbon component of particulate matter (PM) with aerodynamic diameter less than or equal to 2.5 microns (PM2.5). This is the size of PM that most strongly absorbs light and thus has potential radiative forcing effects (i.e., potential to contribute to global warming). Potential climate forcing impacts resulting from BC emissions include direct, albedo (i.e., fraction of solar energy hitting the earth that is reflected), and other effects. BC is emitted with other particles (e.g. organic carbon) and criteria pollutants such as nitrogen and sulfur dioxides. Though some of these co-pollutants may exert a cooling effect on climate, the net effects of BC emissions likely contribute to global climate warming. Appendix B shows the 20 year global warming potential and black carbon equivalent values used in the results calculation. Results are presented here based on BC equivalents. The highest BC impacts are seen for charcoal briquettes, which tend to have high particulate matter emissions when processed in a kiln and also when combusted. Similarly, high emissions of particulate matter are seen for use of firewood in traditional stoves. Utilization of the liquid and gas fuels result in the lowest overall BC impacts. Some life cycle stages have negative BC equivalent impacts, which is the case when emissions of SO_x and organic carbon, pollutants with net cooling effects on the climate, are greater than the emissions of BC and other co-emitted pollutants that lead to short term warming impacts.

Table A-71. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (Ghana)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	3.39	3.39
Processed Solid Biomass	Charcoal Briquettes from Wood	0	7.07	0.0061	1.33	8.40
	Charcoal Briquettes from Bamboo	0	6.89	0.0061	1.33	8.22
	Non-Carbonized Briquettes from Sawdust	0	0.017	0.0061	2.35	2.37
	Non-Carbonized Briquettes from Crop Residues	0	-1.4E-04	2.0E-06	4.17	4.17
	Wood Pellets	0	-0.0072	0.0034	0.10	0.10
	Wood Chips	0	0.0011	6.6E-05	1.53	1.53
Liquid/Gas	Ethanol from Sugarcane	3.4E-04	-0.0014	-0.0044	0.014	0.0084
	Ethanol from Wood	0	0.0082	9.8E-04	0.014	0.023
	Biogas from Dung	0	0	0	0.051	0.051
	LPG	0.038	-0.0015	-2.5E-04	0.047	0.083

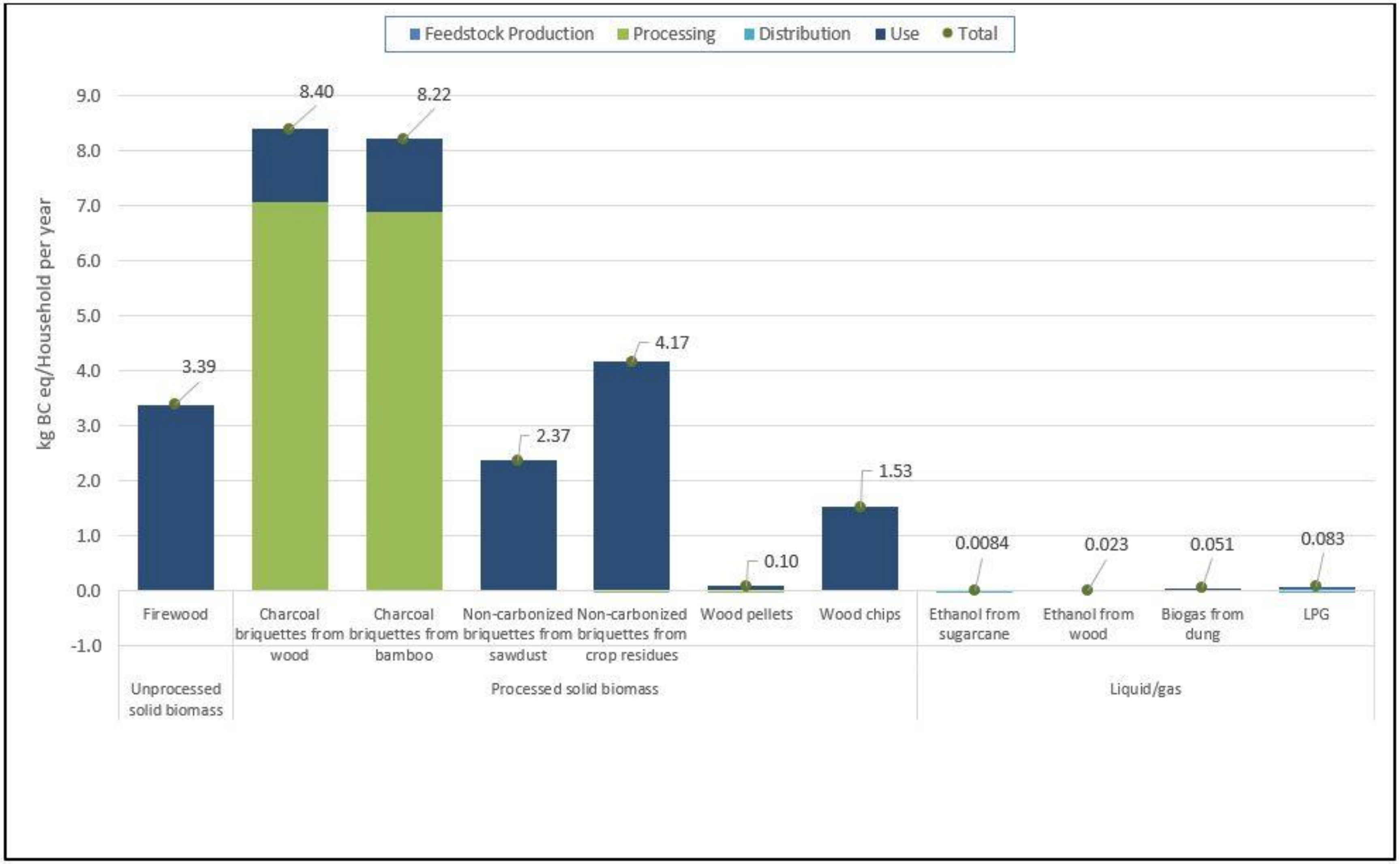


Figure A-65. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (Ghana)
To produce, distribute and use cooking fuels by a single household per year

A.7.2.5 Particulate Matter Formation Potential

Table A-72 and Figure A-66 show the particulate matter formation impact results for fuels in Ghana by life cycle stage. Particulate matter can contribute to many negative health impacts such as effects on breathing and respiratory systems, damage to lung tissue, cancer, and premature death. Primary and secondary pollutants leading to particulate matter formation as well as PM2.5 are characterized here to kg PM10 eq. Charcoal briquettes lead to the greatest particulate matter formation impacts, followed by briquettes from crop residues/sawdust and firewood. For charcoal briquettes, the carbonization of the wood in the kiln dominates the overall life cycle impacts. Charcoal briquettes from bamboo have slightly lower particulate matter impacts than wood charcoal briquettes. This is because a larger portion of bamboo charcoal briquettes are estimated to be produced in hot-tail kilns; whereas, all wood charcoal in Ghana is assumed to be produced in traditional earth mound kilns. Advanced liquid fuels as well as biogas and wood pellets have comparably small particulate matter impacts.

Table A-72. Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (Ghana)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	11.5	11.5
Processed Solid Biomass	Charcoal Briquettes from Wood	0	27.9	0.16	3.46	31.6
	Charcoal Briquettes from Bamboo	0	27.0	0.16	3.46	30.6
	Non-Carbonized Briquettes from Sawdust	0	0.91	0.16	8.01	9.08
	Non-Carbonized Briquettes from Crop Residues	0	0.0015	5.3E-05	19.5	19.5
	Wood Pellets	0	0.083	0.089	0.51	0.68
	Wood Chips	0	0.018	0.0017	5.23	5.25
Liquid/Gas	Ethanol from Sugarcane	0.16	0.0078	0.059	0.0021	0.23
	Ethanol from Wood	0	0.30	0.025	0.0021	0.33
	Biogas from Dung	0	0	0	0.26	0.26
	LPG	0.32	0.025	0.0030	0.24	0.59

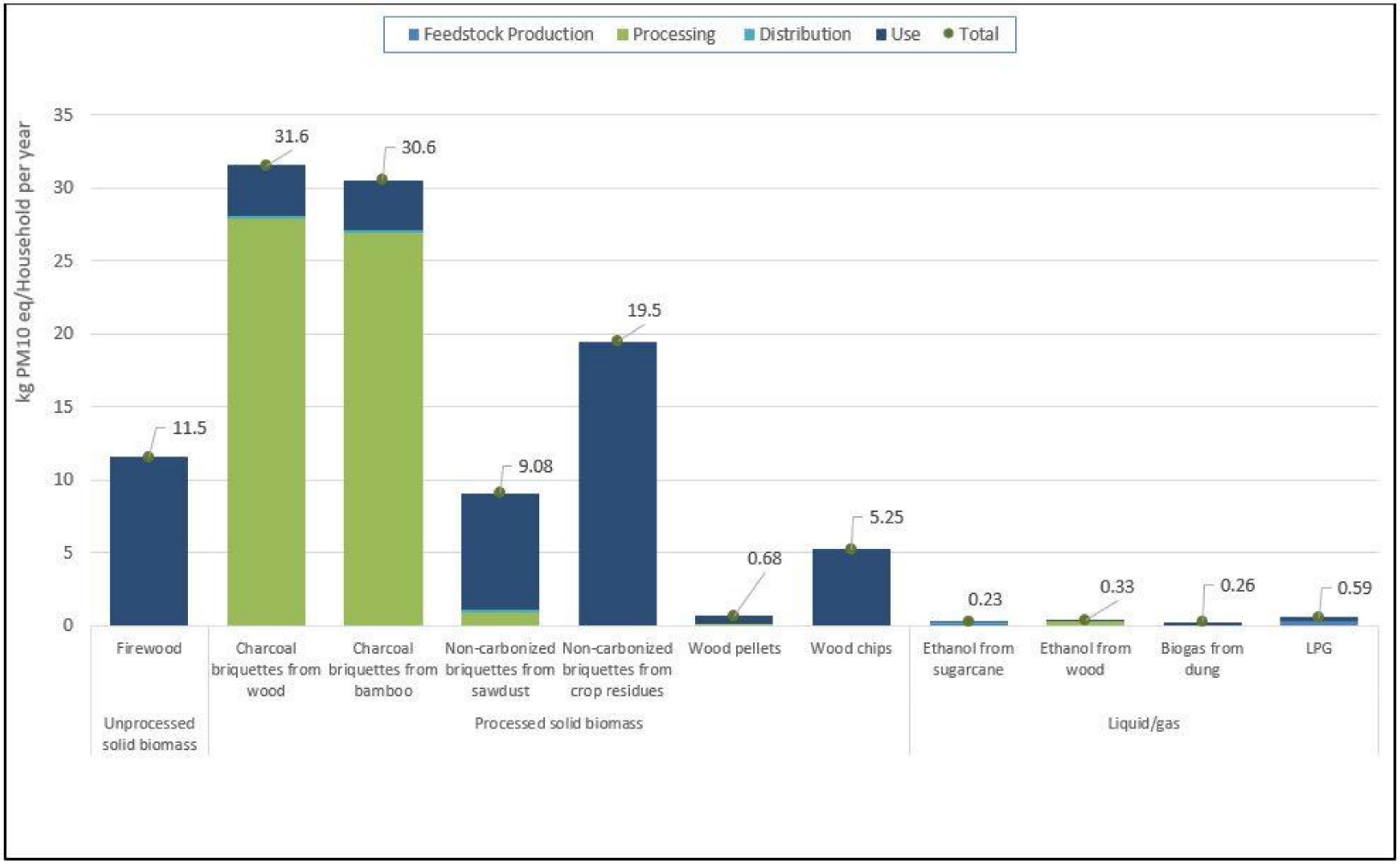


Figure A-66. Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (Ghana)
To produce, distribute and use cooking fuels by a single household per year

A.7.2.6 Fossil Fuel Depletion

Table A-73 and Figure A-67 provide the fossil fuel depletion impact results for fuels in Ghana by life cycle stage. Fossil depletion captures the consumption of fossil fuels, primarily coal, natural gas, and crude oil. All fuels are normalized to kg oil eq based on the heating value of the fossil fuel relative to the heating value of a kg of oil. The fossil depletion associated with firewood as well as biogas and ethanol from wood is negligible, as these fuels are not derived from fossil fuel, and collection of these fuels is done manually. While biomass fuels are not derived from fossil fuels, some fossil fuels may be consumed across the life cycle of these fuels for energy inputs to fuel production and processing, distribution, and disposal. Fossil depletion for wood pellets is associated with electricity usage for pelletization and some transport, while sugarcane ethanol fossil depletion is primarily from fertilizers during cane production, as well as diesel for farm operation and distribution of the feedstock and fuel. Some fossil depletion impacts are also seen for processing the wood chips and non-carbonized briquettes for the portions of these fuels that are not processed manually (as discussed in detail in Appendix B, 3% of non-carbonized and carbonized wood/bamboo briquetting is modeled as mechanized in Ghana, and 100% of wood chipping is modeled as mechanized in Ghana). Fossil depletion impacts are highest for LPG as this source of energy relies on fossil fuels.

Table A-73. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (Ghana)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed solid biomass	Firewood	0	0	0	0.033	0.033
Processed solid biomass	Charcoal briquettes from wood	0	0.036	0.029	0.0020	0.067
	Charcoal briquettes from bamboo	0	0.0070	0.029	0.0020	0.038
	Non-carbonized briquettes from sawdust	0	0.28	0.029	0.017	0.33
	Non-carbonized briquettes from crop residues	0	0.39	9.8E-06	0.013	0.40
	Wood pellets	0	21.6	0.017	8.9E-04	21.6
	Wood chips	0	1.40	3.2E-04	0.015	1.42
Liquid/gas	Ethanol from sugarcane	9.39	0.39	2.71	0	12.5
	Ethanol from wood	0	5.30	0.0047	0	5.31
	Biogas from dung	0	0	0	0	0
	LPG	104	493	1.20	204	803

Figure A-67. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (Ghana)

To produce, distribute and use cooking fuels by a single household per year

A.7.2.7 Water Depletion

Table A-74 and Figure A-68 illustrate the water depletion impact results for fuels in Ghana by life cycle stage. Water depletion results are based on the volume of fresh water inputs over the life cycle of the assessed fuels. Water may be incorporated in the fuel product, evaporated, or returned to the same or different water body or to land. If the water is returned to the same water body, it is assumed the water is returned at a degraded quality, and therefore is considered consumptive use. Water consumption includes evaporative losses from establishment of hydroelectric dams but does not include the water passing through the turbine, since that water is not removed from its source. The hydropower in the electricity mix drives the overall water depletion impacts. Water depletion associated with wood pellets, the fuel with the highest water consumption impacts, is due to electricity usage during palletization (with 67% of the electricity grid mix in Ghana from hydropower).[244] Electricity also drives the minimal water depletion impacts for the 3% of briquettes pressed with motorized machines in Ghana. Water depletion impacts are also notable for sugarcane ethanol, as some irrigation is required for the cane production. Some water depletion impacts are also seen for the biogas to maintain the digester, but these are negligible when compared to the evaporative losses from hydropower in the electricity grid. Some water inputs are required for the production of LPG during crude oil extraction and petroleum refining. Water depletion impacts are negligible for the traditional biomass fuels (i.e. firewood), which are not irrigated. Because the water content of these fuels comes from the atmosphere as rainfall, the water released back to the atmosphere when the biomass is dried or combusted is not considered consumptive use.

Table A-74. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (Ghana)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	0.25	0.25
Processed Solid Biomass	Charcoal Briquettes from Wood	0	1.13	2.8E-04	0.015	1.14
	Charcoal Briquettes from Bamboo	0	1.13	2.8E-04	0.015	1.14
	Non-Carbonized Briquettes from Sawdust	0	13.0	2.8E-04	0.13	13.2
	Non-Carbonized Briquettes from Crop Residues	0	18.0	9.4E-08	0.10	18.1
	Wood Pellets	0	953	1.6E-04	0.0044	953
	Wood Chips	0	1.45	3.1E-06	0.11	1.57
Liquid/Gas	Ethanol from Sugarcane	77.2	1.86	1.60	0	80.6
	Ethanol from Wood	0	1.38	4.5E-05	0	1.38
	Biogas from Dung	0	15.9	0	0	15.9
	LPG	26.8	10.5	36.4	0	73.8

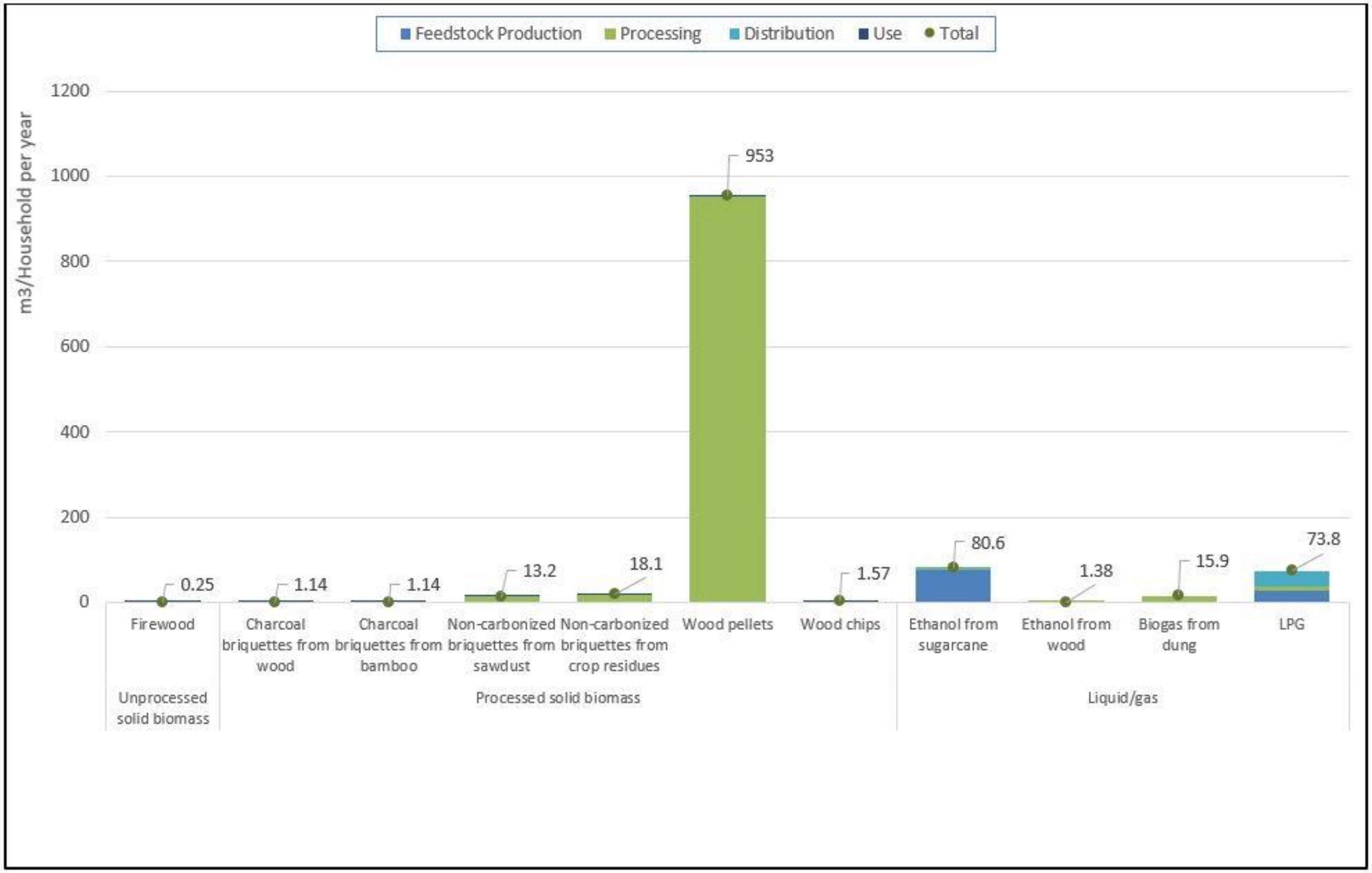


Figure A-68. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (Ghana)

To produce, distribute and use cooking fuels by a single household per year

A.7.2.8 Terrestrial Acidification Potential

Table A-75 and Figure A-69 show the terrestrial acidification potential impact results for fuels in Ghana by life cycle stage. Terrestrial acidification quantifies the acidifying effect of substances on their environment. Important contributing emissions include SO_2, NO_x, and NH_3. Electricity usage for pelletization drive biomass pellet acidification impacts. Sulfur dioxide emissions from coal in the electricity grid are notably higher than sulfur dioxide emissions from combustion of other fuels. Ethanol contains no sulfur, so there are no sulfur dioxide emissions, a main cause of acidification, for the ethanol cookstove use stage. However, there are notable NOx emissions leading to acidification for the portion cane straw burned on the field. Firewood has the highest overall acidification impacts. The main contributing emissions leading to acidification potential for the traditional fuels are SO_x and NO_x. For instance, NO_x leads to 73% and SO_x leads to 27% of the firewood acidification impacts, respectively. Distribution acidification impacts in Ghana are highest for transportation of the carbonized and non-carbonized briquettes since a greater mass of input fuel for the solid biomass is required to be transported a longer distance given the proximity of end users to forests in Ghana (Appendix B provides detailed discussions of the model's transportation parameters). Distribution impacts are also notable for sugarcane ethanol, which is assumed to be transported via ocean freighter from Brazil, the world's largest producer of sugarcane ethanol.[327] The lowest overall acidification impacts are seen for biogas. Because land applied digested sludge from biogas production is used by another product system, it is considered to be outside the system boundaries for this analysis; however, it is possible that this land applied digested sludge could lead to emissions of ammonia, an acidifying substance.

Table A-75. Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (Ghana)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total
		Feedstock Production	Processing	Distribution	Use	
Unprocessed Solid Biomass	Firewood	0	0	0	2.72	2.72
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.25	0.38	0.51	1.14
	Charcoal Briquettes from Bamboo	0	0.24	0.38	0.51	1.13
	Non-Carbonized Briquettes from Sawdust	0	0.018	0.38	1.89	2.29
	Non-Carbonized Briquettes from Crop Residues	0	0.0050	1.3E-04	1.06	1.07
	Wood Pellets	0	0.28	0.21	0.17	0.66
	Wood Chips	0	0.036	0.0041	1.23	1.27
Liquid/Gas	Ethanol from Sugarcane	0.79	0.032	0.19	0	1.01
	Ethanol from Wood	0	0.36	0.061	0	0.42
	Biogas from Dung	0	0	0	0.076	0.076
	LPG	0.74	0.075	0.010	0.44	1.26

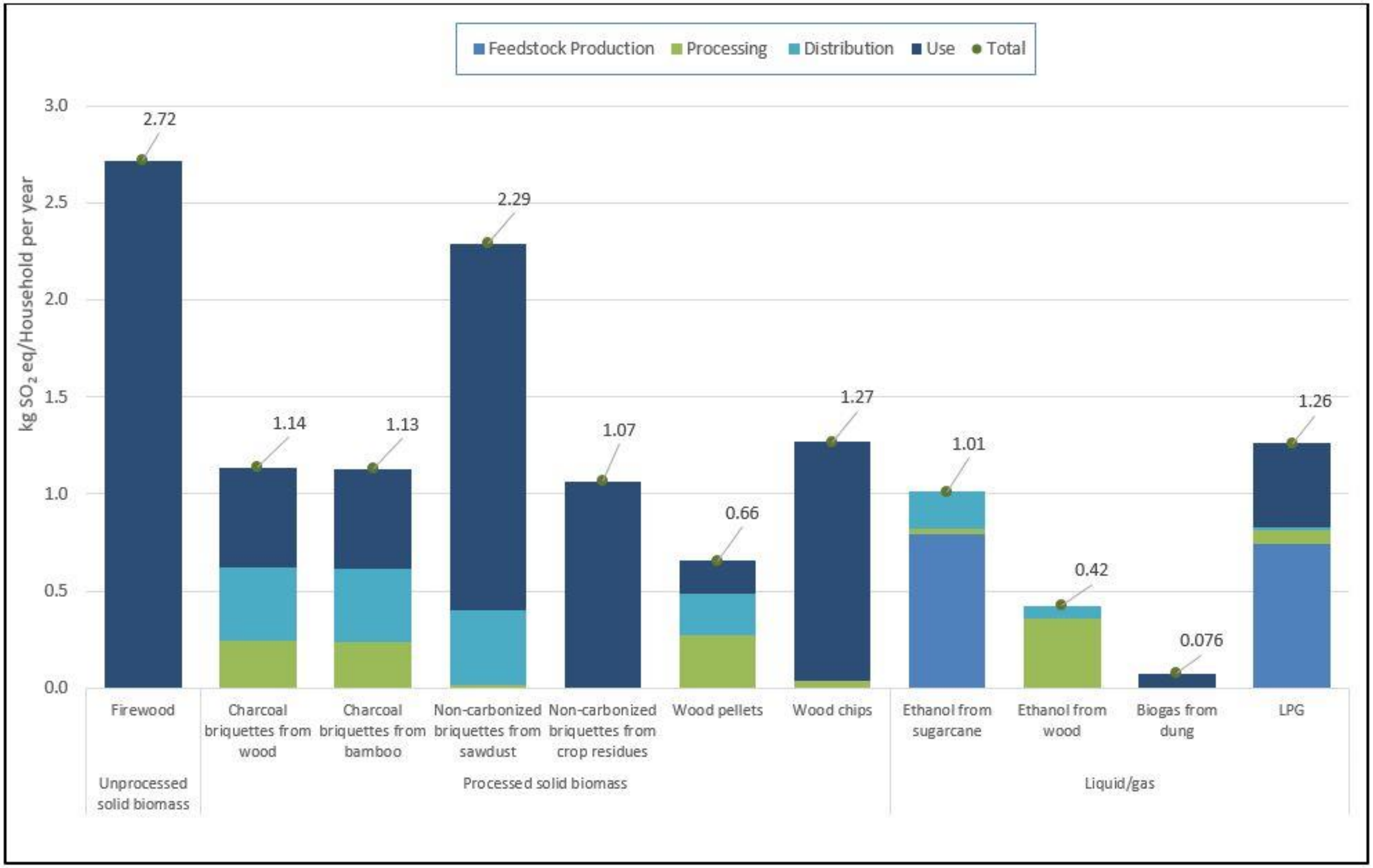


Figure A-69. Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (Ghana)
To produce, distribute and use cooking fuels by a single household per year

A.7.2.9 Freshwater Eutrophication Potential

Table A-76 and Figure A-70 provide the freshwater eutrophication potential impact results for fuels in Ghana by life cycle stage. Eutrophication assesses the impacts from excessive load of macro-nutrients to the environment and eventual deposition in freshwater, which can result in algal blooms, oxygen depletion, and fish kills. Pollutants contributing to this category are all P based (e.g. phosphate, phosphoric acid, phosphorus). Firewood results in the highest eutrophication potential impacts. This is due to the larger ash quantity produced from Firewood compared to all other fuels. The ash from the firewood, which contains phosphorus is assumed to be land applied, which leads to soil emissions and eventual runoff into freshwater. Ash production is also the reason other processed biomass fuels have a relatively high eutrophication impact, with wood combustion at the charcoal kiln leading to the relatively high eutrophication of charcoal briquettes. The non-carbonized processed biomass fuels have slightly lower eutrophication potential impacts than traditional unprocessed biomass fuels. Because processed biomass burns more efficiently than unprocessed biomass, less fuel must be burned, leading to an overall lower quantity of ash produced. While impacts are comparably smaller for ethanol, there are some eutrophication impacts occurring from use of phosphorus based fertilizer in sugarcane production. There are no eutrophication impacts associated with biogas. Application of the digested sludge from the biogas system would likely lead to some eutrophication impacts, but utilization of this useful co-product is outside the system boundaries of this study. The digested sludge impacts are allocated to the product system it serves (i.e. nutrients for crop production). Impacts from fossil based fuels and biomass pellets are minimal compared to the traditional fuels.

Table A-76. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (Ghana)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	0.82	0.82
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.34	3.1E-07	0.049	0.39
	Charcoal Briquettes from Bamboo	0	0.33	3.1E-07	0.049	0.38
	Non-Carbonized Briquettes from Sawdust	0	0.0031	3.1E-07	0.42	0.42
	Non-Carbonized Briquettes from Crop Residues	0	2.8E-05	1.1E-10	0.32	0.32
	Wood Pellets	0	0.0017	1.8E-07	0.014	0.016
	Wood Chips	0	2.1E-04	3.5E-09	0.37	0.37
Liquid/Gas	Ethanol from Sugarcane	0.039	2.5E-04	2.2E-04	5.3E-06	0.040
	Ethanol from Wood	0	1.1E-05	5.2E-08	5.3E-06	1.6E-05
	Biogas from Dung	0	0	0	0	0
	LPG	0.0044	0.0014	5.0E-05	0	0.0059

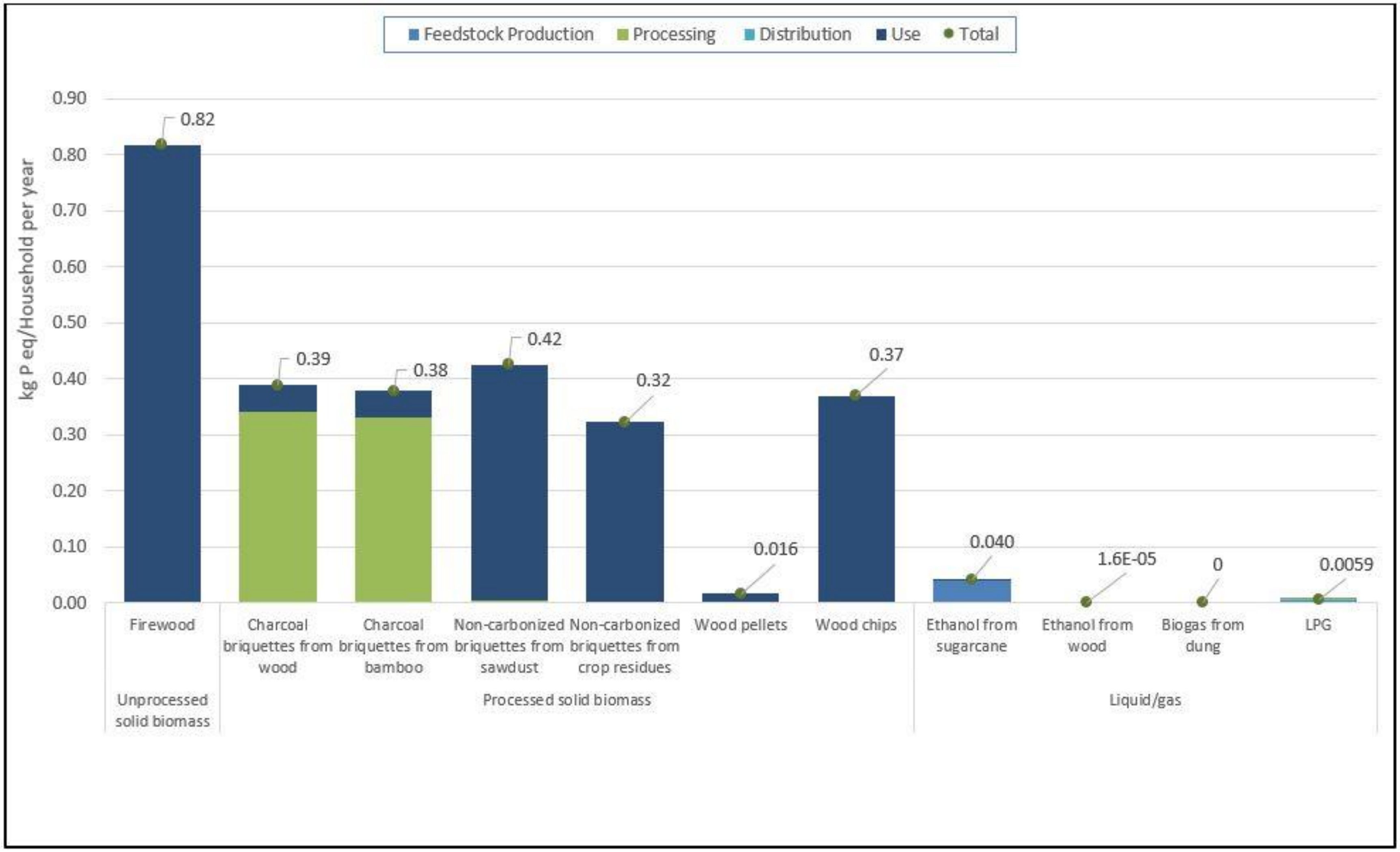


Figure A-70. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (Ghana)
To produce, distribute and use cooking fuels by a single household per year

A.7.2.10 Photochemical Oxidant Formation Potential

Table A-77 and Figure A-71 present the photochemical oxidant formation potential impact results for fuels in Ghana by life cycle stage. The photochemical oxidant formation (i.e. smog formation) results are an indicator of the potential for formation of reactive substances that cause harm to human health and vegetation. Results are characterized here to kg of non-methane volatile organic compounds (NMVOC) eq. Some key emissions for cookstove fuel systems that contribute to photochemical oxidant formation include carbon monoxide, methane, nitrogen oxides, NMVOCs, and sulfur dioxide. Firewood and charcoal briquettes lead to the greatest photochemical formation impacts, followed by processed biomass fuels. For charcoal briquettes, impacts are dominated by the fuel processing stage (carbonization in a kiln). Photochemical oxidant formation impacts are relatively small for the liquid fuels, processed non-carbonized biomass and biogas.

Table A-77. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (Ghana)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	123	123
Processed Solid Biomass	Charcoal Briquettes from Wood	0	116	0.65	23.9	141
	Charcoal Briquettes from Bamboo	0	115	0.65	23.9	140
	Non-Carbonized Briquettes from Sawdust	0	0.63	0.65	85.2	86.5
	Non-Carbonized Briquettes from Crop Residues	0	0.0036	2.2E-04	15.1	15.1
	Wood Pellets	0	0.025	9.8E-06	0.51	0.53
	Wood Chips	0	0.061	0.0070	55.6	55.7
Liquid/Gas	Ethanol from Sugarcane	3.78	0.0086	0.15	0.31	4.24
	Ethanol from Wood	0	0.63	0.10	0.31	1.04
	Biogas from Dung	0	0	0	0.40	0.40
	LPG	5.38	0.11	0.014	5.25	10.8

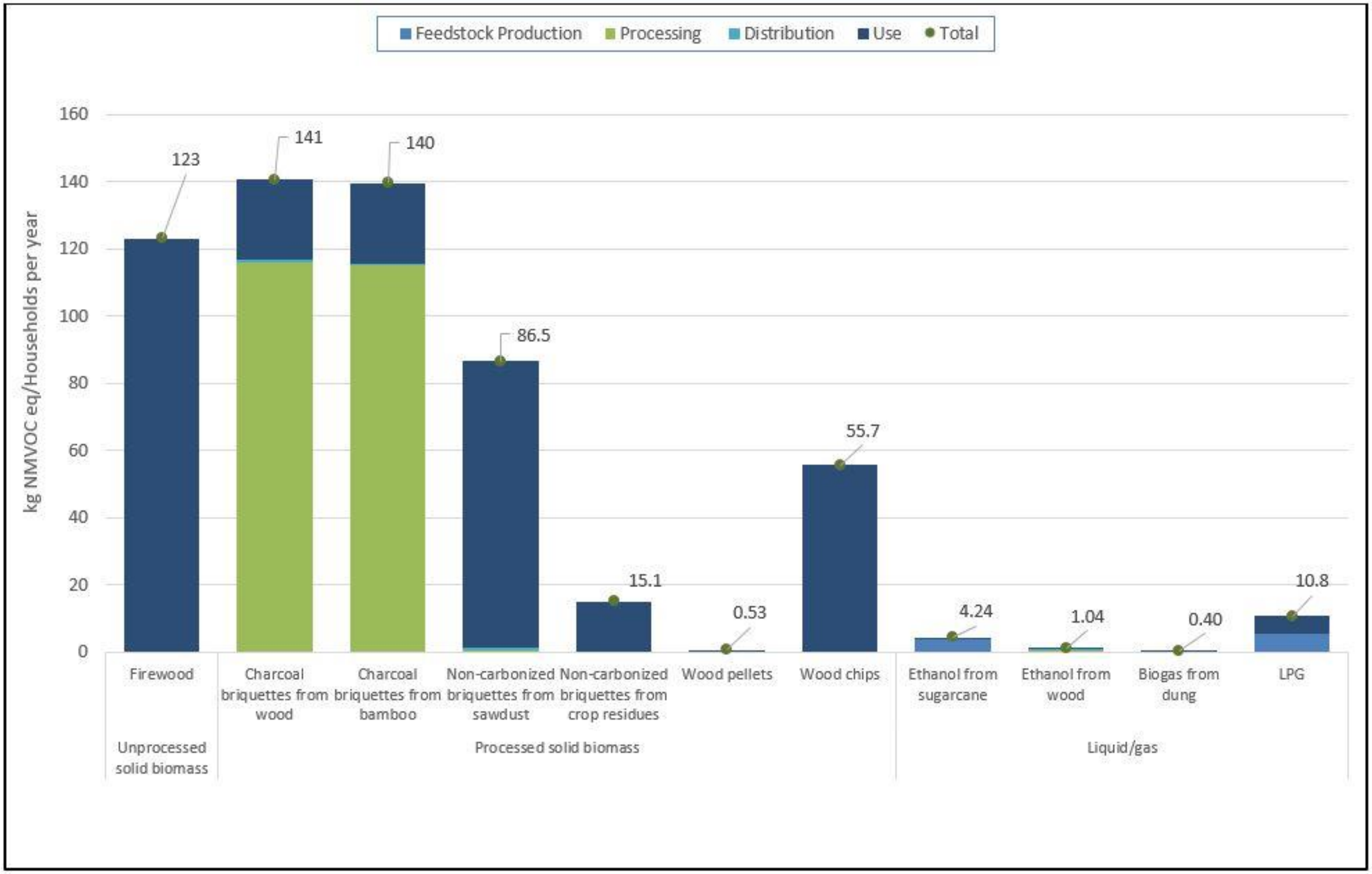


Figure A-71. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (Ghana)
To produce, distribute and use cooking fuels by a single household per year

A.7.3 Economic Indicators for Ghana

A.7.3.1 Fuel Use

Figure A-72 shows a breakout of the percentages of primary cooking fuels used by the population in Ghana. About half the population relies on biomass (primarily firewood), while just over a third uses charcoal and about 10 percent use LPG.[407,408,409] Firewood is most commonly used in rural areas, while LPG and charcoal are mainly used in urban areas. [410,411] Roughly 3 percent of people use other fuels, with wood pellets, bamboo carbonized briquettes, crop residue non-carbonized briquettes, and biogas all being available within the country, although only on the small enterprise scale.[412]

While Figure A-72 people use biomass as their primary cooking fuel, it is worth noting that many people in Ghana use a mix of cooking fuels and stoves, depending on what food they are cooking. In rural areas in particular, there might be one stove inside and one stove outside.[413]

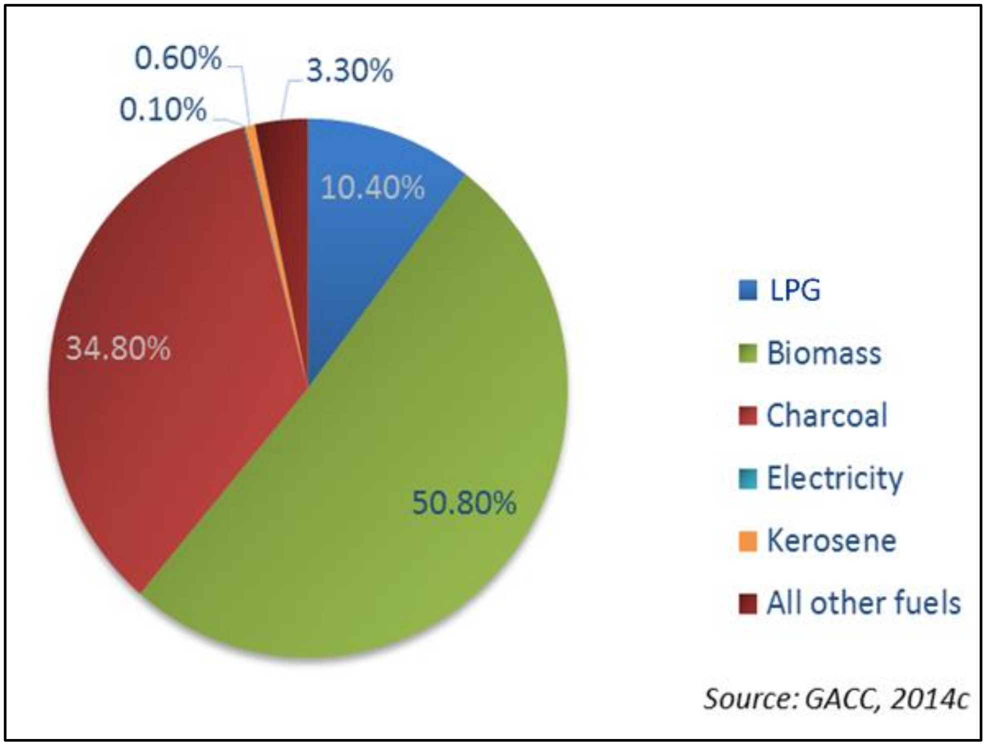


Figure A-72. Current Cooking Fuel Mix in Ghana

A.7.3.2 Fuel Imports, Exports, Production, and Demand in Ghana

Table A-78 shows the levels of imports, exports, production, and demand (assumed to be equal to current consumption) of several fuels in Ghana. The data on total and household demand do not differentiate between fuel use for cooking and fuel use for other purposes such as heating. By far the most dominant fuel is firewood, which is almost all consumed within the country, based on the production and export data. Firewood supplies are expected to be affected by the change in forest hectares in Ghana, which has showed a decreasing trend of about two percent per year in recent years.[414] LPG is not as widely used in Ghana as other fuels, with demand of 214,500 tonnes per year, most of which is imported.[415] Some of the LPG that is not consumed by households is used by commercial vehicles.[416] Ghana produces 30,000 tonnes of ethanol, with only about 20 percent of that consumed domestically,[417] primarily for alcoholic beverages.[418]

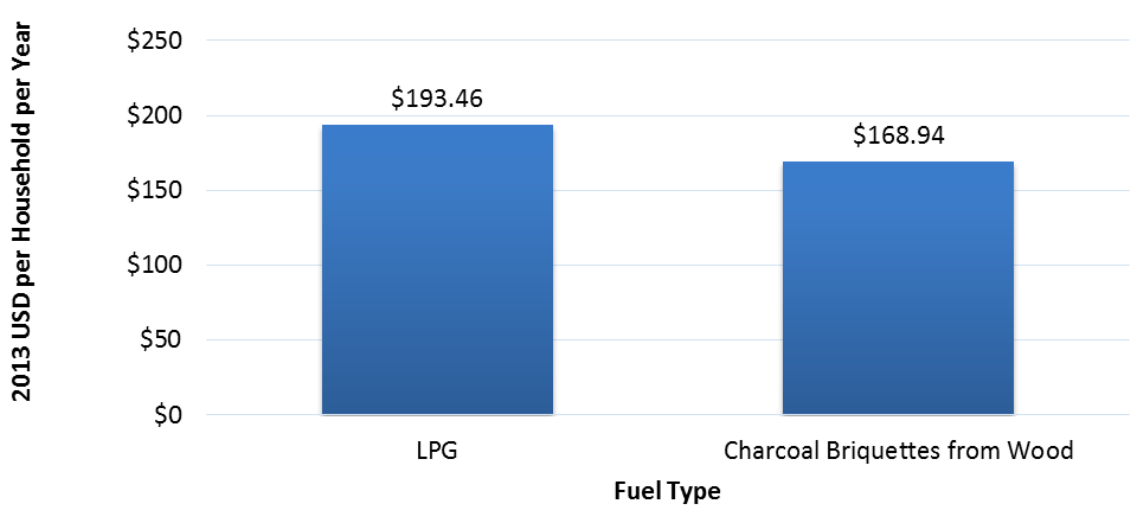
Charcoal is one of the dominant fuels used in Ghana, and most of the 1.2 million tonnes consumed each year is produced domestically and used by households.[419] Other wood fuels, such as pellets and chips, are imported and exported, but no data are available about how much is produced or consumed and for what purpose.

Table A-78. Fuel Imports, Exports, Production, and Demand in Ghana (Tonnes per Year)

Fuel	Imports	Exports	Production	Demand		Sources
				Total	Household	
LPG	177,800	No data	44,600	214,500	104,000	UNSD, 2011
Ethanol	7,472	8,401	28,553	5,727	No data	UNSD, 2013 OECD/FAO, 2014
Firewood	0.01	217	41,448,188	No data	No data	UNSD, 2013 FAO, 2014
Charcoal Briquettes	No data	800	1,233,600	1,232,600	1,134,900	UNSD, 2011
Wood Pellets	No data	182	No data	No data	No data	UNSD, 2013
Wood Chips	69,168	No data	No data	No data	No data	UNSD, 2013

A.7.3.3 Fuel Cost in Ghana

Figure A-73 shows the price per household per year for the cooking fuels in Ghana for which cost data are available. LPG is the most expensive, at close to $200 per household per year, and wood charcoal costs about $170 per household per year.[420,421,422] Without government subsidies, the LPG price would increase by about 50 percent.[423] Firewood in Ghana is generally collected rather than sold on the open market, and so is essentially free, but continuing deforestation will reduce the future supply and could result in the introduction of a firewood market.[424]



Note: No data available for fuel types not included.

Sources: Accenture, 2012b; Matthews & Zeissig, 2011; ECG, 2014

Figure A-73. Fuel Cost Indicator for Cooking Fuels in Ghana

A.7.4 Social Indicators for Ghana

A.7.4.1 Government Policies/Programs

Ghana's government has recently emphasized the importance of sustainable development in the energy sector, most notably through the Strategic National Energy Plan (2006-2020), which outlines goals to increase renewable energy sources to 10 percent nationally by 2020 and increase rural electrification by renewables to 30 percent by 2020.[425] Complementing this plan are the Renewable Energy Act of 2011 and a national bioenergy policy, which "support the development, utilization, and efficient management of renewable energy sources." These policies outline financial mechanisms (feed-in tariffs, a renewable energy fund) and various other initiatives (awareness-raising programming, licensing system for companies working in the renewable energy sector) to "promote and facilitate the sustainable use of biomass" and support other sources of renewable energy.[426] One challenge, however, to Ghana's plans for sustainable development is that Ghana no longer has "least developed country" status with the UN, making it ineligible for Clean Development Mechanism credits, which provide funding for emission reduction projects.[427]

In addition to these considerations, Ghana's government has acknowledged the need to "address the challenge of clean cookstoves…to develop an industry capacity for the standards and accreditation of stoves."[428] Although no cookstove-specific policies were available, high-level government stances related to LPG, ethanol, and charcoal briquettes from wood offer insight into the regulatory landscape surrounding key alternative fuels.

The National Petroleum Authority (NPA) and the Ghana Standards Board regulate LPG manufacturing and end-use safety standards, respectively, but a lack of logistical and human resource capacities of these two regulatory entities has resulted in minimal monitoring of both industry and end-use compliance.[429] The World Bank believes "the capacity of the regulators will have to be strengthened to enable them to establish and enforce relevant laws and regulations for the smooth operation of the LPG industry."[430] Despite these regulatory challenges, as of 2014, the Ghanaian government continues to support the use of LPG. Policies have been put in place to promote the establishment of LPG infrastructure, subsidize fuel and end-use equipment costs, and improve accessibility among middle- and lower-income households in urban, suburban, and rural areas.[431] One market assessment found that without the government's most recent subsidy scheme LPG could be up to 50 percent more expensive (even with the subsidy, however, LPG is still approximately 30 percent more expensive than charcoal on a fuel-only basis).[432] One unforeseen challenge with Ghana's LPG subsidy is that commercial vehicle owners have retrofitted their vehicles to run on LPG, which—when subsidized—is cheaper than gasoline. This resulted in the government planning to phase out the LPG subsidy, though its current status is unknown.[433]

Although ethanol is less widely used than LPG, it also suffers from an identifiable challenge: the market dominance of the alcohol industry. Any ethanol enterprise looking to shift feedstock processing capacity away from alcohol would most likely be inhibited by the legal protections historically afforded to the alcohol industry.[434]

The Ghanaian government has also tried to regulate the production of charcoal briquettes from wood by licensing legitimate enterprises. As with LPG, however, the policies have had an uncertain impact.[435]

A.7.4.2 Supply & Access Challenges

Although over 10 percent of the Ghana population uses LPG, the fuel's availability is limited to urban and peri-urban communities where cost is less of an issue.[436] Even wealthier communities, however, suffer from uncertain LPG supplies from local refineries and inconsistent imports. One study found that consumers sometimes wait as long as two to three days for LPG refills.[437] To combat shortages, some users absorb the cost of additional cylinders to keep on hand to ensure uninterrupted supply, whereas others temporarily switch back to more readily available traditional fuels such as charcoal.[438] Switching fuels in response to unstable LPG supplies generates anxiety, creates inconvenience,[439] and increases expenses as end-users must keep alternative stoves and fuel stores on hand. A key challenge is the poor delivery infrastructure at the government-owned Tema Oil Refinery which results in consistent fuel shortages and operational inefficiencies.[440]

Approximately 65 percent of Ghanaians use a combination of charcoal briquettes and firewood to meet their cookfuel needs[441] and, historically, these fuels have been easily accessible.[442] Users of both fuels, however, are increasingly vulnerable to fuel shortages due to a deforestation rate of about 2 percent per year over recent years.[443] Most at-risk are the approximately 3 million households in Ghana, representing 48 percent of total households, who rely on firewood as their primary fuel. The majority of such households manually collect the firewood they use. Although the impacts of deforestation on firewood availability are not felt across Ghana equally, the lack of commercial networks and supply routes—few consumers of firewood purchase it; those with the ability to pay for cooking energy opt for charcoal and supplement it with manually-collected firewood as necessary[444]—make it difficult to reallocate resources from woodfuel-dense zones such as Kintampo and Nkoranza.[445] Relatedly, charcoal producers must travel farther and farther to find appropriate feedstocks, thus decreasing the fuel's reliability and increasing its cost.[446]

Sustainable wood-based alternatives that also offer more efficient heat delivery than whole firewood are not yet widely available. A small number of companies are producing wood-based pellets and chips, but these fuels are not commercially viable due to their inability to displace charcoal usage. Charcoal's ubiquity tends to keep prices low, and, even when users try out pellets or chips, inconsistent availability leads many to default back to the more reliable charcoal.[447] Other alternatives include charcoal briquettes from bamboo and non-carbonized crop residue briquettes, but production statistics are not currently available for these nascent industries.[448] There is some evidence that crop residue biogas digesters are still in use (repurposed from a defunct initiative to promote biogas use at schools), but it is unclear whether the biogas produced is used for cooking or for other uses such as heating.[449]

A.7.4.3 Distribution & Adoption Challenges

One of the primary challenges to the adoption of clean cooking methods in Ghana is a lack of awareness regarding the costs and benefits of alternative fuels that would help inform household decision-making.[450] For example, a number of respondents to a survey conducted in a Ghanian slum stated they prefer to use firewood to charcoal because it burns faster.[451] Although this view is not reflective of those held by typical decision-makers in Ghana, it illustrates how misinformation regarding alternative fuels can persist among those who would stand to benefit from their adoption.

There are a variety of challenges specific to the adoption of LPG in Ghana. As a specific instance of the limited awareness described above, public knowledge about the lifespan, maintenance, handling, and safety requirements of LPG cylinders is lacking.[452] A more substantial knowledge base would be required both to increase adoption of LPG and to retain users who have already switched. The three other primary challenges associated with LPG use in Ghana are:

1. Limited Infrastructure: The industry is mainly private-sector owned and there is limited infrastructure development in rural and peri-urban areas. Moreover, poorly maintained road networks adversely affect LPG distribution in all settings.

2. Poor Cylinder Management: Many cylinders in circulation are in need of repair or disposal, and it is unclear who is coordinating efforts to maintain the country's cylinder supply.

3. Financial Barriers: LPG adoption requires the high upfront cost for end-use equipment, the high recurrent cost of filling large cylinders, and the expenses associated with traveling from rural communities to urban areas where LPG outlets are located.[453] Underscoring these aspects of LPG adoption, a study of 8,686 households in Ghana concluded that LPG was positively correlated with income.[454]

Although not necessarily a challenge to fuel adoption, understanding potential taste changes is an important step in understanding Ghana's cookfuel use landscape. For example, LPG is used for soups, stews, and other foods that need to be kept warm, whereas charcoal and wood are used outside for meals that require more intense heat and take longer to cook.[455] In some cases, firewood is the preferred cookfuel because it can be used with traditional stoves, which are often best-equipped for the vigorous stirring associated with traditional foods such as tuo zaafi (a porridge made from grain flour), banku (a cooked mixture of corn and cassava doughs), boiled yams, and more.[456]

A.7.4.4 Protection & Safety

According to available data, there are three leading safety concerns in Ghana. The first relates to collecting wood far distances from home. Traveling to remote locations exposes people to encounters with animals such as venomous snakes and, even if such encounters are avoided, the manual gathering of wood is taxing and can cause severe physical strain.[457] The second leading concern relates to the use of traditional fuels in certain urban settings. Wooden structures predominate in many Ghanaian slums, leading to a perceived (and actual) risk of fire associated with burning firewood. One survey showed that this risk led almost 50 percent of households located in slums to prefer charcoal.[458] The final perceived safety risk is associated with cylinder-based fuels as a significant portion of Ghanaians perceive LPG as inherently dangerous.[459]

A.7.4.5 Time & Drudgery

In Ghana, the bulk of the fuel collection and cooking burden falls on women and children.[460] On average, women spend three times longer collecting firewood daily than their male counterparts,[461] spending between 37 to 44 minutes per day depending on their community's proximity to firewood supplies. This multiplies out to approximately 2.2 million hours per year spent by Ghanaian women collecting fuel.[462] Moreover, for children who help with fuel collection, most of the gathering is done by hand before school, taking away from time that could otherwise be spent resting or preparing for school.[463] A similar pattern exists for cooking, where women spend upwards of 100 minutes per day on meal preparation alone.[464] Although the data necessary for comparing these firewood collection and cooking times to specific alternative fuels are not available, anecdotal evidence suggests that any cooking fuel that can be collected/purchased and cooked with more efficiently has a great opportunity to improve quality of life.[465]

A.7.4.6 Income Earning Opportunities

The two primary income earning opportunities in Ghana for cookstove fuels are in the LPG and charcoal briquette from wood sectors. Ghana was recently selected by the Millennium Challenge Corporation to receive a $547 million poverty-reduction project. Although the assistance budget is intended for agriculture and transportation development, funding in these two arenas will provide a substantial benefit to the LPG sector. Agriculture development will increase the purchasing power of the rural population, thus increasing demand for LPG outside of its normal, urban markets. Transportation development will improve Ghana's supply infrastructure, improving the consistency and speed at which LPG can be delivered.[466]

The United Nations Development Programme's (UNDP) recent decision to investigate sustainable charcoal value chains in Ghana also indicates a substantial income earning opportunity. The program will seek to develop new briquette technologies, institute effective licensing systems, and improve labeling for cookstoves.[467] Such an initiative has the opportunity to create 200 to 350 job-days per terajoule consumed, a high number compared to 80 to110 job-days for electricity, 10 to 20 for LPG, and 10 for kerosene.[468] While the labor expenses associated with a high job-day per terajoule consumed fuel potentially indicate a more expensive, less affordable fuel, in the case of wood-based charcoal briquettes, it is estimated that more employment will be generated among the rural poor (in the form of manual charcoal production, truck driving, miscellaneous contract labor, etc.) than their urban counterparts,[469] who would presumably command higher incomes and put upward pressure on fuel prices. Although the UNDP effort would focus on charcoal briquettes from wood, there are an estimated seven to ten companies in existence that make briquettes from other sources[470] which could also benefit from increased sectoral funding.

One such alternative feedstock for charcoal briquettes is bamboo. There are an estimated 300 small enterprises producing charcoal briquettes from bamboo in Ghana with a market of approximately 7,000 households.[471] As deforestation continues to deplete Ghana's forests, business opportunities for nontraditional charcoal feedstocks such as bamboo will likely continue to expand.

A.7.4.7 Opportunities for Women Along the Value Chain

According to the Global Alliance for Clean Cookstoves 2013 Results Report, the clean cookstove industry in Ghana currently has 107 employees (19 percent of whom are women) and 1,140 microentrepreneurs (57 percent of whom are women).[472] Evidence from successful women-owned small-to-medium-sized enterprises suggests that LPG wholesale and retail might provide strong opportunities for women.[473,474] For example, M38 is a woman-owned LPG retail businesses in Ghana that as of 2012 has paid off its startup loan, employs four people, and is planning to establish an additional LPG filling station using its own capital.[475] Anecdotal evidence indicates that opportunities in LPG processing and distribution, on the other hand, tend to be dominated by men due to the historical exclusion of women from jobs that are perceived as labor intensive[476] Following a similar pattern, there are opportunities for women in charcoal wholesale and retail, but production tends to be dominated by men.[477,478] Regardless of the fuel being promoted, any initiative looking to better integrate women into the Ghanaian cookfuel sector should be mindful of cultural barriers which have historically restricted women to certain traditional economic activities[479] and resulted in women doing more than 80 percent of the household work, even when they bring home all the income.[480] Understanding, without necessarily endorsing, these cultural patterns has the potential to help new enterprises improve the gender balance of their workforces by creating opportunities for women that are progressive and forward-looking, but conscious of traditional social pressures that continue to inform Ghanaian livelihoods.

A.8 Detailed Results for Kenya

A.8.1 Overview of Kenya

Kenya is the seventh largest country by population in Africa, with 78 percent of the population living in rural areas and 22 percent in urban areas in 2015.[481] Over two-thirds of the population rely on some form of unprocessed biomass as their cooking fuel.

Adequate supply of fuel resources is an important consideration, as there may not be adequate feedstocks to sustainably support current or increasing levels of wood fuel use. Kenya has shown an overall trend of an approximately 0.5 percent decrease in forest land per year over recent years,[482] and forest cover has been reduced to between 2 and 6 percent of total land area. Although not the only cause, firewood harvested for fuel is a significant driver of deforestation.[483] Market assessments suggest that deforestation due to logging will increasingly threaten Kenya's economy, water supply, and ecosystems.[484] In addition to decreasing forest land, some regions are experiencing desertification where dry lands become increasingly arid. The arid and semi-arid lands are home to about 35 percent of the country's population and constitute about 80 percent of Kenya's total land.[485] Drought is a common occurrence in these areas, reducing vegetative cover and affecting the quality of the rangelands.[486] Eighty percent of Kenya is reported to be prone to desertification in recent years.[487] These issues threaten the use of other biomass fuels.

Fuel cost is another key issue. Many households in rural areas can collect firewood for free, although availability is decreasing. Firewood is purchased by 40 percent of rural users and 71 percent of peri-urban users.[488] The fuel price is higher in urban areas and subject to seasonal fluctuations.[489]

Households across Kenya generally eat similar foods and have the same cooking habits. Tea and porridge are two popular hot beverages and food, which require intense heat for boiling water. Rural households use three-stone fires and traditional cook stoves. Most kitchens are in separate huts and are usually poorly ventilated.[490] Cooking fires may serve multiple secondary purposes, such as providing heat or light for the home, heating water for bathing, preserving food (by drying above or near the fire), and socializing. Changes to the cooking fuel or type of cookstove would likely require the household to use other fuels for these functions.

The following sub-sections address the environmental, economic, and social considerations related to cooking fuels and stoves for Kenya in greater detail.

A.8.2 Environmental Indicators for Kenya

This section covers the detailed Kenya LCA results for the ten environmental indicators assessed for each fuel. The stove thermal efficiency by fuel and the fuel heating values employed in this study to calculate the LCA results are provided in Table A-79 and Table A-80, respectively. The remainder of this section presents results for each environmental indicator.

Table A-79. Stove Thermal Efficiency Applied by Fuel for Kenya

Fuel Type	Stove Thermal Efficiency	Sources
Firewood	15.0%	GACC, 2010
Charcoal Briquettes from Wood	18.0%	Afrane & Ntiamoah, 2011
Charcoal Briquettes from Bamboo	18.0%	Afrane & Ntiamoah, 2011
Non-Carbonized Briquettes from Sawdust	20.33%	GACC, 2015a Urban Uganda, 2015
Non-Carbonized Briquettes from Crop Residues	31.0%	GACC, 2015a
Wood Pellets	53.0%	Jetter et al., 2012
Wood Chips	31.0%	GACC, 2015a
Ethanol from Sugarcane	53.0%	Aprovecho Research Center, 2009
Ethanol from Wood	53.0%	Aprovecho Research Center, 2009
Biogas from Dung	55.0%	Afrane & Ntiamoah, 2011
LPG	57.0%	Afrane & Ntiamoah, 2011

Table A-80. Fuel Heating Values for Kenya

Fuel Type	HHV (MJ/kg)	Sources
Firewood	16.0	GACC, 2010
Charcoal Briquettes from Wood	25.72	Afrane & Ntiamoah, 2011
Charcoal Briquettes from Bamboo	25.72	Afrane & Ntiamoah, 2011
Non-Carbonized Briquettes from Sawdust	18.8	Davies et al., 2012 Ferguson, 2012
Non-Carbonized Briquettes from Crop Residues	15.6	Simonyan & Fasina, 2013 FAO, 2015 Phyllis2, 2015
Wood Pellets	17.94	Singh et al., 2014 Jetter et al., 2012
Wood Chips	16.0	GACC, 2010
Ethanol from Sugarcane	28.3	Aprovecho Research Center, 2009
Ethanol from Wood	28.3	Aprovecho Research Center, 2009
Biogas from Dung	17.71	Afrane & Ntiamoah, 2011
LPG	45.84	Afrane & Ntiamoah, 2011

A.8.2.1 Total Energy Demand

Table A-81 and Figure A-74 display the total energy demand impact results for fuels in Kenya by life cycle stage. Total energy demand sources consist of non-renewable fuels (natural gas, petroleum, coal, and nuclear) and "renewable" fuels (e.g. biomass, hydro). Energy demand tracks all energy inputs across the life cycle of the fuel, with energy impacts shown at the point of use of the relevant fuel.

The total energy demand results are largely a function of the fuel heating value and thermal efficiency of the fuel and stove combination (Table A-80 and Table A-79). Stoves with higher efficiencies (e.g., LPG, biogas, ethanol, and biomass pellets) have a lower total energy demand overall, because more of the heating value of the fuel is converted into useful cooking energy and therefore less fuel must be produced, transported, and burned to deliver the same amount of cooking energy.

A number of observations can be made regarding energy results for the various types of fuels. For sugarcane ethanol, the feedstock energy results include not only the energy value of the sugar that is converted to ethanol but also the energy content of the bagasse, which provides the majority of energy used to process the sugarcane to ethanol. A co-benefit of ethanol production is the production of electricity, which may be exported. As discussed in the Appendix B methodology, this model employs the cut-off allocation methodology; therefore, a credit is not given here to the sugarcane or wood ethanol for exported electricity, so the energy demand impacts for ethanol should be considered as the upper bounds for these fuel types.

For wood fuels, the wood pellets and wood chips have a lower total energy demand than traditional firewood. Wood chips and wood pellets typically have a lower moisture content, greater energy content, and greater surface area than the traditional solid biomass, which allows the fuel to combust more efficiently. It is also more common to see improved cookstoves, which have higher stove thermal efficiencies, used in combination with the wood chips and wood pellets in Kenya.

For briquettes, the energy demand impact for the carbonized briquettes from wood and bamboo is relatively higher compared to other fuels due to the lower stove efficiencies for metal charcoal briquette stoves in Kenya and the charcoal kiln energy impacts. That is, additional energy is consumed when burning firewood at the kiln to produce charcoal briquettes prior to charcoal briquette utilization in a cookstove. Similarly, in processing the commercially made non-carbonized sawdust briquettes (3% of sawdust briquettes are assumed to be produced commercially in Kenya), sawdust is combusted to remove the moisture content of the briquettes, which contributes to the relatively higher total energy demand of the sawdust briquettes compared to other non-carbonized processed biomass fuels. The remaining 97% of sawdust briquettes are modeled as pressed manually and dried naturally to 10% moisture content. This requires 1.5 kg wood input to each 1 kg briquette, assuming a 40% moisture content of the original greenwood.[173]

Overall, liquid and gas fuels as well as processed solid biomass fuels not requiring additional combustion of solid fuel for processing (e.g., wood pellets) lead to the lowest overall total energy demand impacts.

Table A-81. Total Energy Demand (MJ) for Cooking Fuel Types (Kenya)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed solid biomass	Firewood	0	0	0	30,433	30,433
Processed solid biomass	Charcoal briquettes from wood	0	34,524	0.032	25,347	59,871
	Charcoal briquettes from bamboo	0	33,559	0.032	25,347	58,906
	Non-carbonized briquettes from sawdust	0	12,164	2.13	22,442	34,609
	Non-carbonized briquettes from crop residues	0	19.0	3.8E-04	14,591	14,610
	Wood pellets	0	2,863	0.42	8,608	11,472
	Wood chips	0	67.2	0.011	14,718	14,785
Liquid/gas	Ethanol from sugarcane	445	20,544	89.6	8,608	29,687
	Ethanol from wood	0	1,058	0.12	8,608	9,667
	Biogas from dung	0	0	0	8,079	8,079
	LPG	2,460	19,493	37.7	8,004	29,995

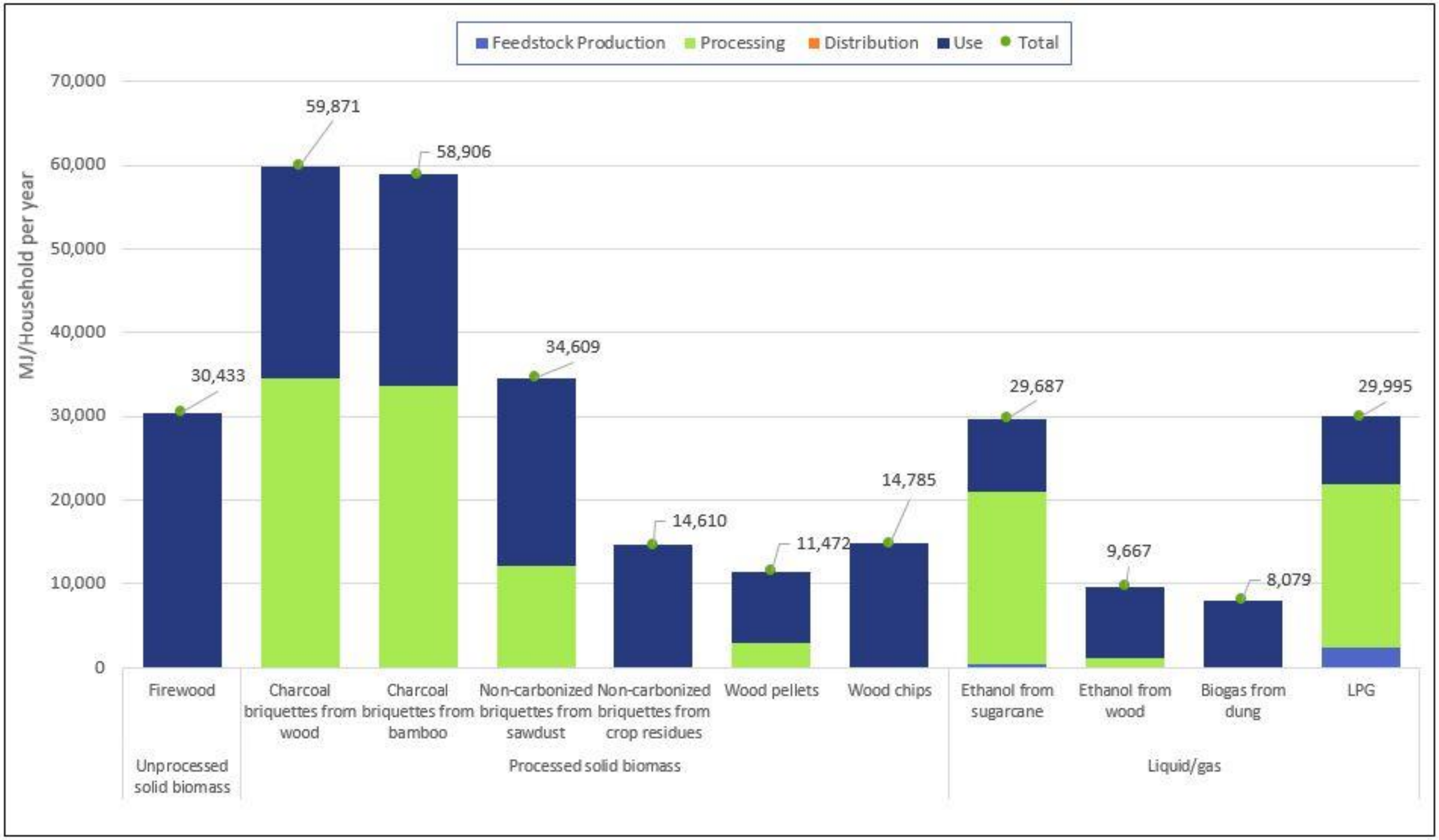


Figure A-74. Total Energy Demand (MJ) for Cooking Fuel Types (Kenya)
To produce, distribute and use cooking fuels by a single household per year

A.8.2.2 Net Energy Demand

Table A-82 and Figure A-75 illustrate the net energy demand impact results for fuels in Kenya by life cycle stage. Net energy demand is calculated in the same way as total energy demand, with the final energy delivered to the cooking pot deducted from the results. The net energy indicator is, therefore, the additional energy required for the life cycle of the cookstove fuel beyond what is delivered to the consumer for cooking purposes. For Kenya, 12.5 MJ of cooking energy are consumed per household per day, which equates to 4,563 MJ per household per year.[491, 404] Utilization of firewood consumes approximately seven times more energy than is provided to the pot, as listed in the last column of Table A-82. Similar levels of net energy demand are seen for non-carbonized briquettes from sawdust, and LPG. The lowest overall net energy demand is calculated for non-carbonized briquettes from crop residues, wood pellets, wood chips, ethanol, and biogas from dung. Production, processing, distribution, and use of these less energy intensive fuels uses 0.77 to 2.24 times the amount of energy delivered to the pot. Charcoal briquettes result in the highest net energy demand due to the lower yield at the kilns in African countries as compared to countries investigated in other world regions. For Kenya, 3.2 kg of wood are required for 1 kg charcoal output at the earth mound kiln.[492] Energy impacts are also higher for petroleum refining in Africa as compared to other world regions modeled, resulting in the notable net energy demand burdens of LPG.[327]

Table A-82. Net Energy Demand (MJ) for Cooking Fuel Types (Kenya)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total	Net Energy Consumed: Delivered Energy
		Feedstock Production	Processing	Distribution	Use		
Unprocessed solid biomass	Firewood	0	0	0	25,870	25,870	5.67
Processed solid biomass	Charcoal briquettes from wood	0	34,524	0.032	20,785	55,309	12.1
	Charcoal briquettes from bamboo	0	33,559	0.032	20,785	54,344	11.9
	Non-carbonized briquettes from sawdust	0	12,164	2.13	17,880	30,046	6.59
	Non-carbonized briquettes from crop residues	0	19.0	3.8E-04	10,029	10,048	2.20
	Wood pellets	0	2,863	0.42	4,046	6,909	1.51
	Wood chips	0	67.2	0.011	10,155	10,222	2.24
Liquid/gas	Ethanol from sugarcane	445	20,544	89.6	4,046	25,124	5.51
	Ethanol from wood	0	1,058	0.12	4,046	5,104	1.12
	Biogas from dung	0	0	0	3,516	3,516	0.77
	LPG	2,460	19,493	37.7	3,442	25,432	5.57

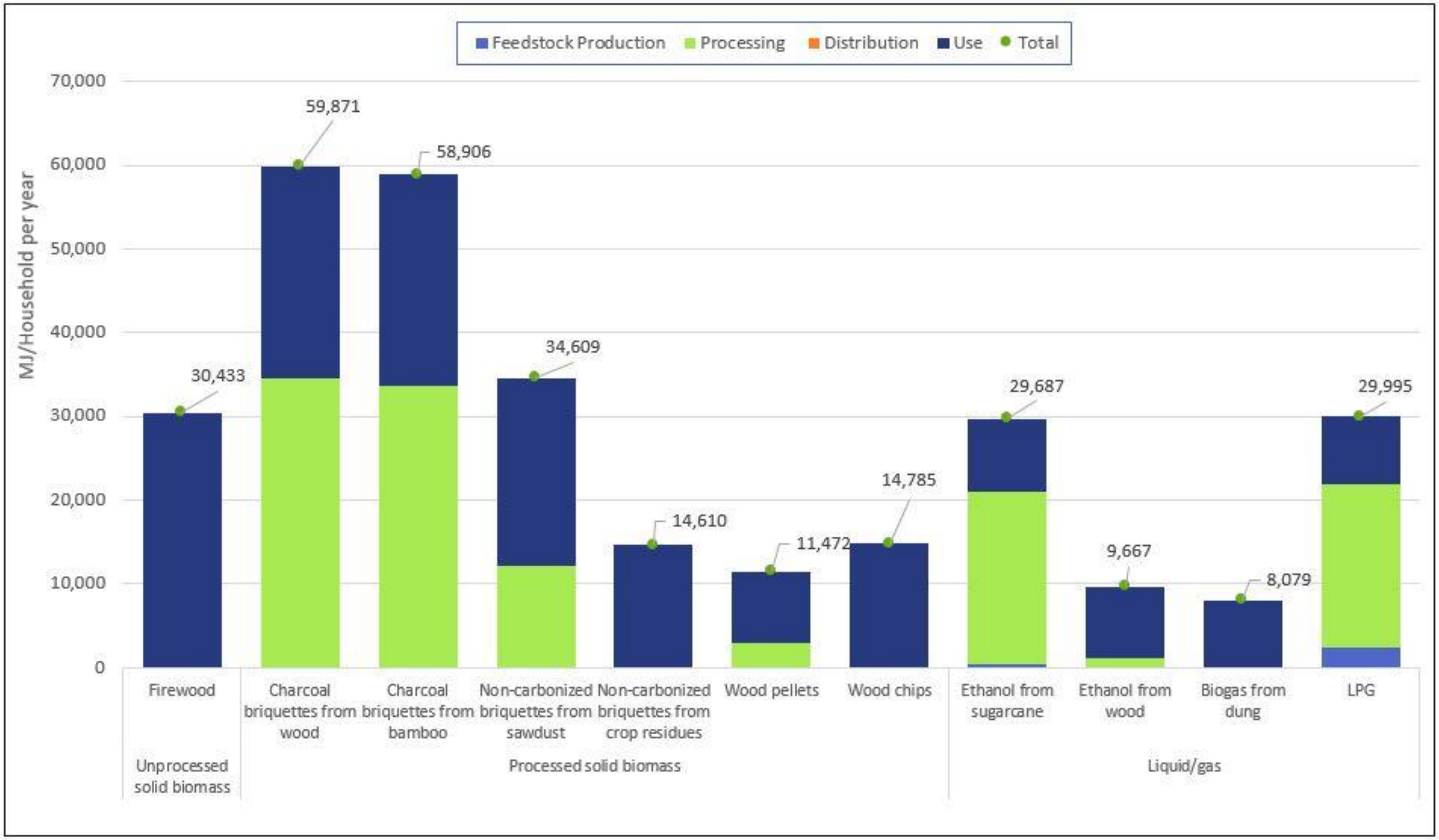


Figure A-75. Net Energy Demand (MJ) for Cooking Fuel Types (Kenya)
To produce, distribute and use cooking fuels by a single household per year

A.8.2.3 Global Climate Change Potential (100a)

Table A-83 and Figure A-76 present the GCCP impact results for fuels in Kenya by life cycle stage. The GCCP impact category represents the heat trapping capacity of greenhouse gases over a 100 year time horizon. Fossil fuel GCCP impacts are dominated by combustion emissions in the cookstove use stage.

Biogas GCCP impacts are primarily from methane leakage during the production of biogas in an anaerobic digester (1% of biogas escapes as fugitive emissions at the digester).[493] Sugarcane ethanol, crop residue briquettes, and charcoal briquettes from bamboo are derived from renewable biomass that removed CO_2 from the atmosphere during growth; therefore, the CO_2 emissions released from combustion of these fuels is considered carbon neutral, as discussed in detail in the Appendix B methodology. Impacts for these renewable fuels during the use phase are driven by nitrous oxide and methane emissions during cookstove use. Impacts associated with fertilizer production and emissions from application also play a role in the sugarcane ethanol overall impacts.

Based on the decreasing trend in forest area in Kenya, all of the wood harvested for use as cooking fuel is considered unsustainably sourced, and the combustion emissions for the non-sustainable use of wood are not considered carbon-neutral. This adjustment is also applied to other wood fuels (wood-derived charcoal briquettes, wood pellets and wood chips), but not to fuels derived from wood wastes (wood ethanol and non-carbonized briquettes from sawdust). With the cut-off modeling methodology used in this analysis, wood wastes are treated as a “free” product (all burdens are allocated to the primary wood product, e.g., lumber, which is outside the scope of this study), so emissions of biomass CO_2 for fuels derived from wood waste are treated as carbon neutral. For charcoal briquettes, GCCP impacts for carbonization of the wood in the kiln are higher in magnitude than the emissions from combustion of the charcoal briquettes in a cookstove. Charcoal kiln impacts are largely driven by the methane emissions during the carbonization process. Combustion emissions for bamboo-derived charcoal briquettes are lower than for wood-derived charcoal briquettes because bamboo is a renewable crop and all combustion emissions are considered carbon-neutral, while none of the wood combustion emissions are considered carbon-neutral, since the wood supply in Kenya is considered non-renewable based on the decreasing forest area. All GHGs associated with the production and combustion of LPG, including CO_2 emissions from cooking, are considered fossil-derived and accounted for in the GCCP impacts.

Table A-83. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (Kenya)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	3,422	3,422
Processed Solid Biomass	Charcoal Briquettes from Wood	0	2,692	55.9	2,652	5,400
	Charcoal Briquettes from Bamboo	0	1,226	55.9	405	1,686
	Non-Carbonized Briquettes from Sawdust	0	3.15	157	345	505
	Non-Carbonized Briquettes from Crop Residues	0	0.84	0.028	207	208
	Wood Pellets	0	53.5	31.3	1,564	1,649
	Wood Chips	0	3.79	0.80	1,659	1,663
Liquid/Gas	Ethanol from Sugarcane	364	24.1	6.40	4.36	399
	Ethanol from Wood	0	22.4	8.97	4.36	35.7
	Biogas from Dung	0	1.85	0	11.8	13.6
	LPG	199	48.2	9.03	1,273	1,529

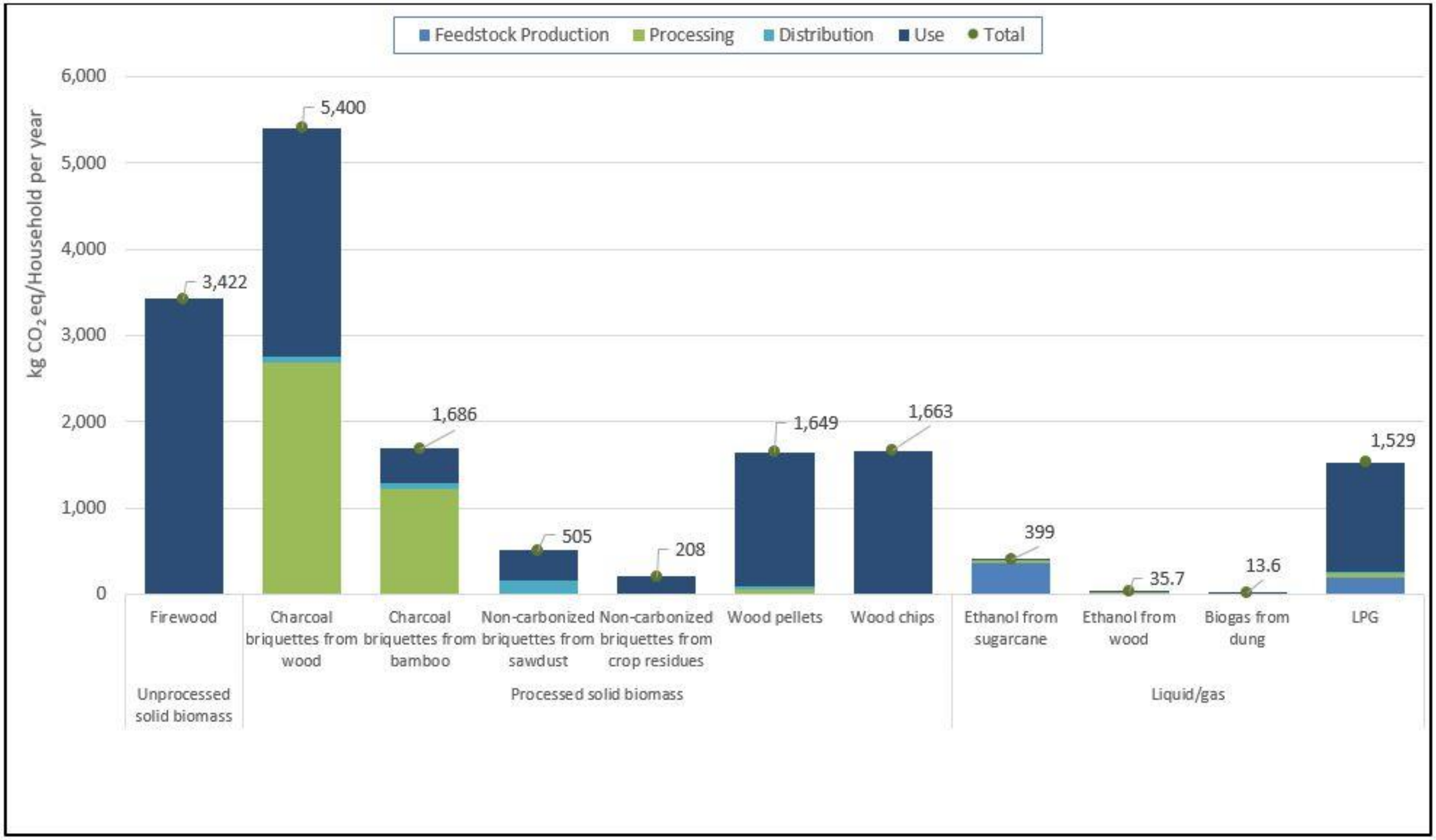


Figure A-76. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (Kenya)
To produce, distribute and use cooking fuels by a single household per year

A.8.2.4 Black Carbon and Short-Lived Climate Pollutants

Table A-84 and Figure A-77 display the black carbon and short-lived climate pollutants impact results for fuels in Kenya by life cycle stage. Black carbon (BC) is formed by incomplete combustion of fossil and bio-based fuels. BC is the carbon component of particulate matter (PM) with aerodynamic diameter less than or equal to 2.5 microns (PM2.5). This is the size of PM that most strongly absorbs light and thus has potential radiative forcing effects (i.e., potential to contribute to global warming). Potential climate forcing impacts resulting from BC emissions include direct, albedo (i.e., fraction of solar energy hitting the earth that is reflected), and other effects. BC is emitted with other particles (e.g. organic carbon) and criteria pollutants such as nitrogen and sulfur dioxides. Though some of these co-pollutants may exert a cooling effect on climate, the net effects of BC emissions likely contribute to global climate warming. Appendix B shows the 20 year global warming potential and black carbon equivalent values used in the results calculation. Results are presented here based on BC equivalents. The highest BC impacts are seen for charcoal briquettes, which tend to have high particulate matter emissions when processed in a kiln and also when combusted. Similarly, high emissions of particulate matter are seen for use of firewood in traditional stoves. Utilization of the liquid and gas fuels result in the lowest overall BC impacts. Some life cycle stages have negative BC equivalent impacts, which is the case when emissions of SO_x and organic carbon, pollutants with net cooling effects on the climate, are greater than the emissions of BC and other co-emitted pollutants that lead to short term warming impacts.

Table A-84. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (Kenya)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	2.91	2.91
Processed Solid Biomass	Charcoal Briquettes from Wood	0	6.44	0.0037	1.22	7.66
	Charcoal Briquettes from Bamboo	0	6.28	0.0037	1.22	7.51
	Non-Carbonized Briquettes from Sawdust	0	0.016	0.011	2.16	2.19
	Non-Carbonized Briquettes from Crop Residues	0	-8.8E-05	1.9E-06	3.83	3.83
	Wood Pellets	0	-0.0044	0.0021	0.095	0.093
	Wood Chips	0	0.0012	7.5E-05	0.50	0.50
Liquid/Gas	Ethanol from Sugarcane	-0.0079	-0.033	-0.0034	0.013	-0.032
	Ethanol from Wood	0	0.0075	6.0E-04	0.013	0.021
	Biogas from Dung	0	0	0	0.047	0.047
	LPG	0.013	-0.025	2.9E-04	0.044	0.031

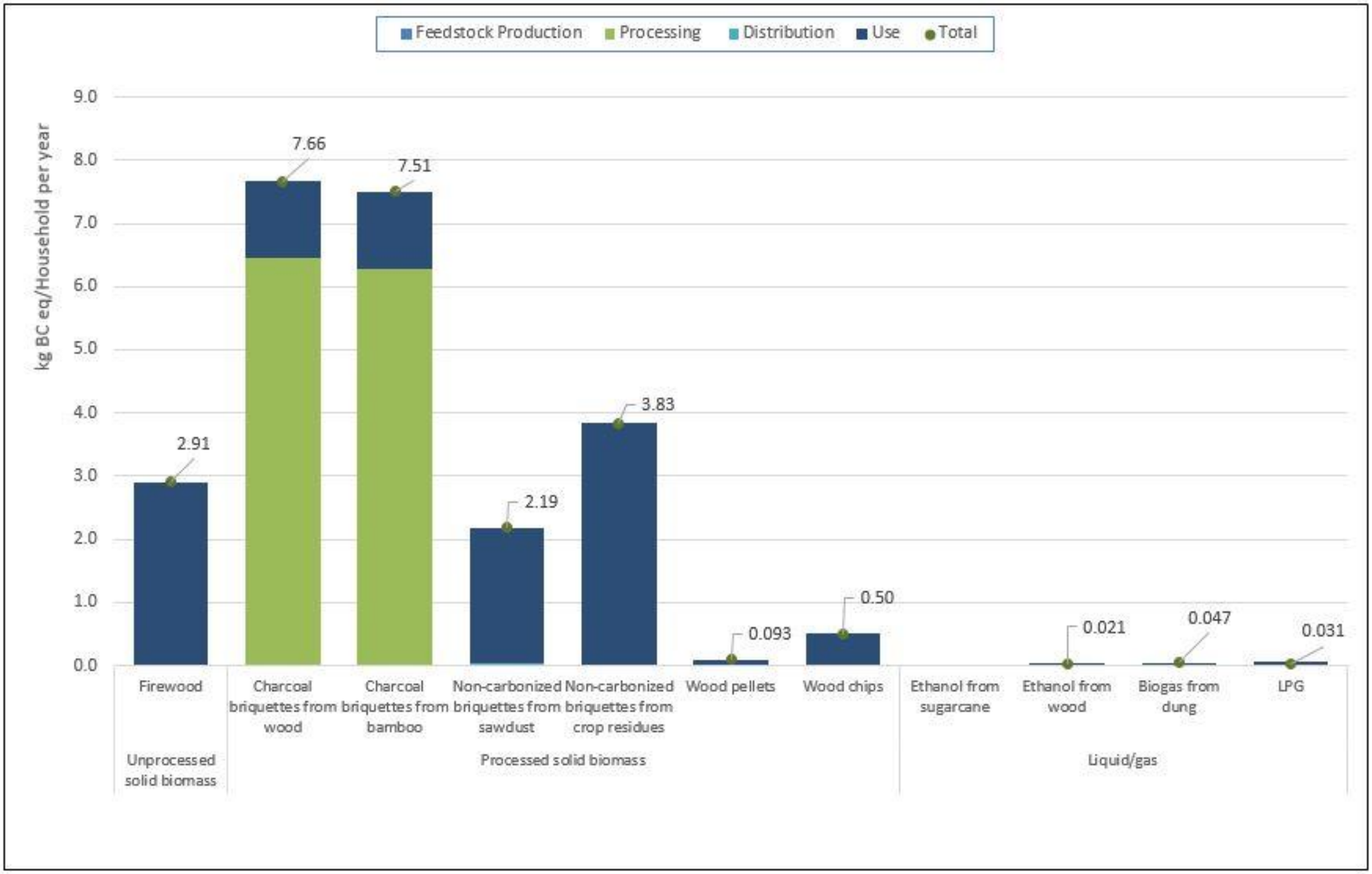


Figure A-77. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (Kenya)
To produce, distribute and use cooking fuels by a single household per year

A.8.2.5 Particulate Matter Formation Potential

Table A-85 and Figure A-78 show the particulate matter formation impact results for fuels in Kenya by life cycle stage. Particulate matter can contribute to many negative health impacts such as effects on breathing and respiratory systems, damage to lung tissue, cancer, and premature death. Primary and secondary pollutants leading to particulate matter formation as well as PM2.5 are characterized here to kg PM10 eq. Charcoal briquettes lead to the greatest particulate matter formation impacts, followed by briquettes from crop residues/sawdust and firewood. For charcoal briquettes, the carbonization of the wood in the kiln dominates the overall life cycle impacts. Charcoal briquettes from bamboo have slightly lower particulate matter impacts than wood charcoal briquettes. This is because a larger portion of bamboo charcoal briquettes are estimated to be produced in hot-tail kilns; whereas, all wood charcoal briquettes in Kenya are assumed to be produced in traditional earth mound kilns. Advanced liquid fuels as well as biogas and wood pellets have comparably small particulate matter impacts.

Table A-85. Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (Kenya)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	9.93	9.93
Processed Solid Biomass	Charcoal Briquettes from Wood	0	25.6	0.097	3.18	28.9
	Charcoal Briquettes from Bamboo	0	24.8	0.097	3.18	28.1
	Non-Carbonized Briquettes from Sawdust	0	0.84	0.27	7.36	8.47
	Non-Carbonized Briquettes from Crop Residues	0	0.0016	4.8E-05	17.9	17.9
	Wood Pellets	0	0.089	0.054	0.47	0.61
	Wood Chips	0	0.014	0.0014	4.81	4.82
Liquid/Gas	Ethanol from Sugarcane	0.52	0.16	0.046	0.0020	0.73
	Ethanol from Wood	0	0.28	0.016	0.0020	0.29
	Biogas from Dung	0	0	0	0.24	0.24
	LPG	0.31	0.34	0.015	0.22	0.89

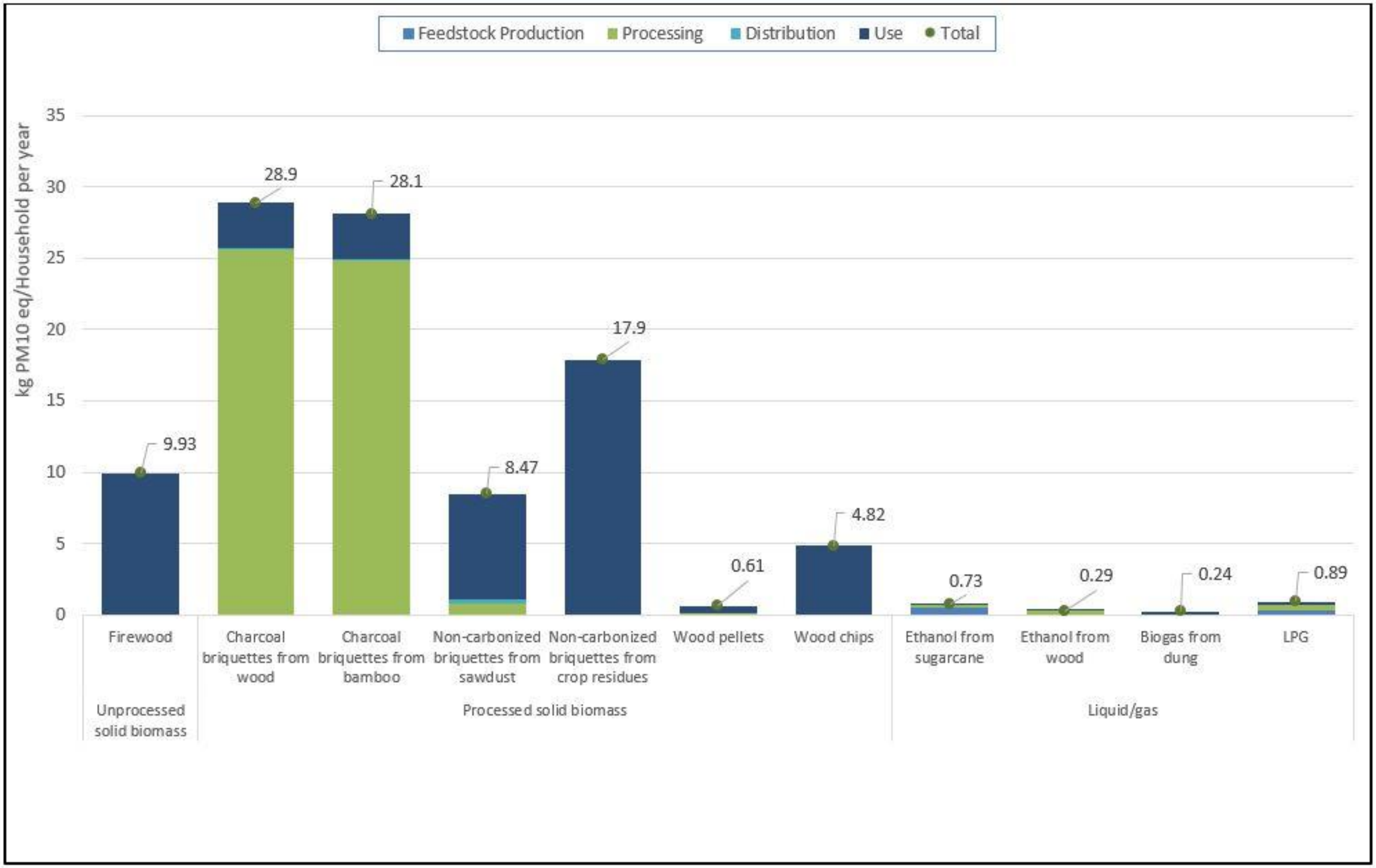


Figure A-78. Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (Kenya)
To produce, distribute and use cooking fuels by a single household per year

A.8.2.6 Fossil Fuel Depletion

Table A-86 and Figure A-79 provide the fossil fuel depletion impact results for fuels in Kenya by life cycle stage. Fossil depletion captures the consumption of fossil fuels, primarily coal, natural gas, and crude oil. All fuels are normalized to kg oil eq based on the heating value of the fossil fuel relative to the heating value of a kg of oil. The fossil depletion associated with firewood as well as biogas and ethanol from wood is negligible, as these fuels are not derived from fossil fuel, and collection of these fuels is done manually. While biomass fuels are not derived from fossil fuels, some fossil fuels may be consumed across the life cycle of these fuels for energy inputs to fuel production and processing, distribution, and disposal. Fossil depletion for wood pellets is associated with electricity usage for pelletization and some transport, while sugarcane ethanol fossil depletion is primarily from fertilizers during cane production, as well as diesel for farm operation and distribution of the feedstock and fuel. Some fossil depletion impacts are also seen for processing the wood chips and non-carbonized briquettes for the portions of these fuels that are not processed manually (as discussed in detail in Appendix B, 3% of non-carbonized and carbonized wood/bamboo briquetting is modeled as mechanized in Kenya, and 28% of wood chipping is modeled as mechanized in Kenya). Fossil depletion impacts are highest for LPG as this source of energy relies on fossil fuels.

Table A-86. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (Kenya)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total
		Feedstock Production	Processing	Distribution	Use	
Unprocessed solid biomass	Firewood	0	0	0	0.025	0.025
Processed solid biomass	Charcoal briquettes from wood	0	0.026	0.018	0.0018	0.046
	Charcoal briquettes from bamboo	0	0.026	0.018	0.0018	0.045
	Non-carbonized briquettes from sawdust	0	0.19	0.051	0.016	0.26
	Non-carbonized briquettes from crop residues	0	0.26	9.0E-06	0.012	0.27
	Wood pellets	0	14.8	0.010	8.2E-04	14.8
	Wood chips	0	1.13	2.6E-04	0.012	1.15
Liquid/gas	Ethanol from sugarcane	55.6	12.8	2.12	0	70.4
	Ethanol from wood	0	4.87	0.0029	0	4.88
	Biogas from dung	0	0	0	0	0
	LPG	58.0	460	0.89	189	708

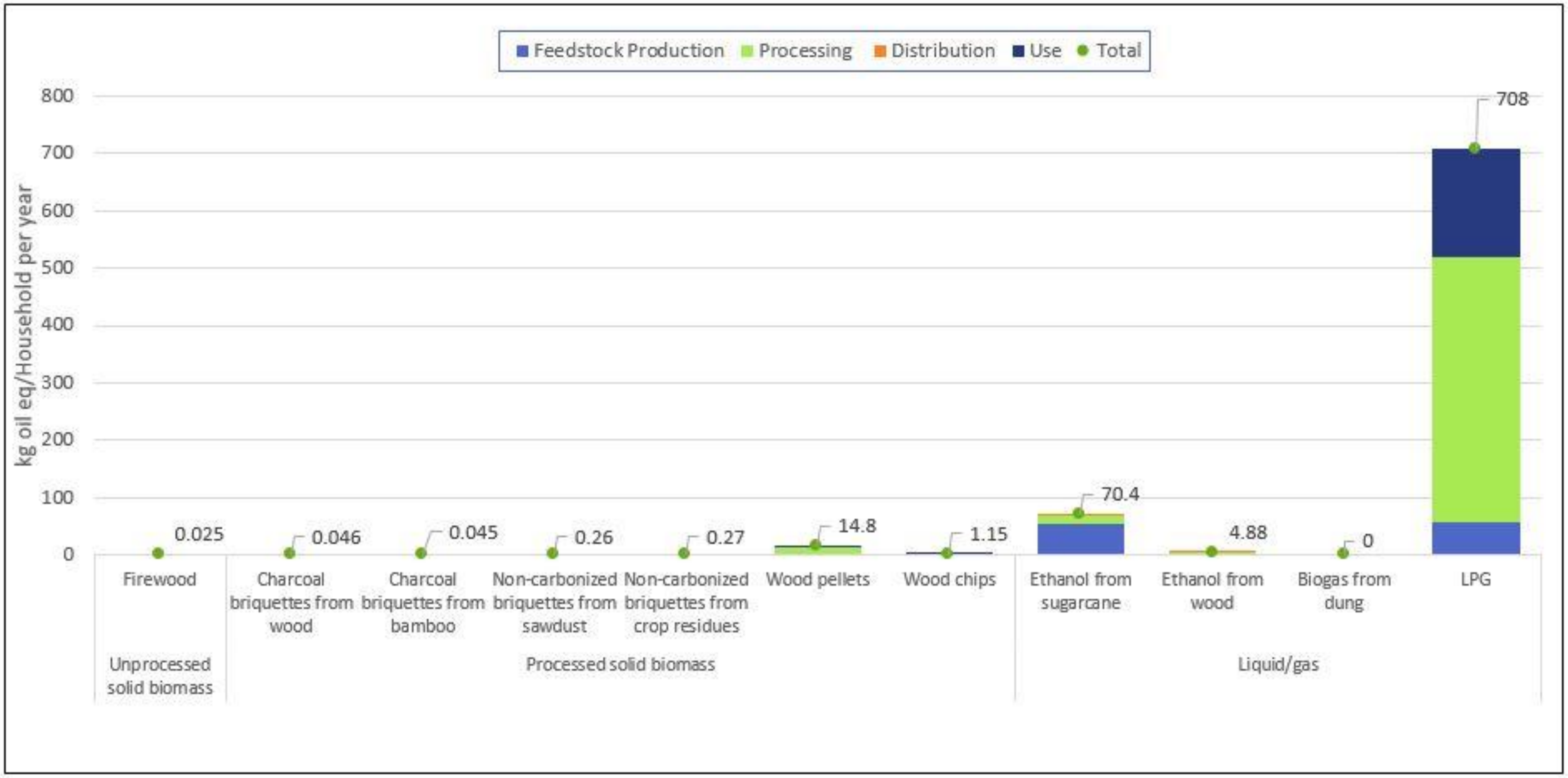


Figure A-79. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (Kenya)
To produce, distribute and use cooking fuels by a single household per year

A.8.2.7 Water Depletion

Table A-87 and Figure A-80 illustrate the water depletion impact results for fuels in Kenya by life cycle stage. Water depletion results are based on the volume of fresh water inputs over the life cycle of the assessed fuels. Water may be incorporated in the fuel product, evaporated, or returned to the same or different water body or to land. If the water is returned to the same water body, it is assumed the water is returned at a degraded quality, and therefore is considered consumptive use. Water consumption includes evaporative losses from establishment of hydroelectric dams but does not include the water passing through the turbine, since that water is not removed from its source. The hydropower in the electricity mix drives the overall water depletion impacts. Water depletion associated with wood pellets, the fuel with the highest water consumption impacts, is due to electricity usage during palletization (with 52% of the electricity grid mix in Kenya from hydropower).[244] Electricity also drives the minimal water depletion impacts for the 3% of briquettes pressed with motorized machines in Kenya. Water depletion impacts are also notable for sugarcane ethanol, as some irrigation is required for the cane production. Some water depletion impacts are also seen for the biogas to maintain the digester, but these are negligible when compared to the evaporative losses from hydropower in the electricity grid. Some water inputs are required for the production of LPG during crude oil extraction and petroleum refining. Water depletion impacts are negligible for the traditional biomass fuels (i.e. firewood), which are not irrigated. Because the water content of these fuels comes from the atmosphere as rainfall, the water released back to the atmosphere when the biomass is dried or combusted is not considered consumptive use.

Table A-87. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (Kenya)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total
		Feedstock Production	Processing	Distribution	Use	
Unprocessed Solid Biomass	Firewood	0	0	0	0.19	0.19
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.75	1.7E-04	0.014	0.77
	Charcoal Briquettes from Bamboo	0	0.75	1.7E-04	0.014	0.76
	Non-Carbonized Briquettes from Sawdust	0	8.53	5.0E-04	0.12	8.65
	Non-Carbonized Briquettes from Crop Residues	0	11.8	8.6E-08	0.092	11.9
	Wood Pellets	0	627	9.7E-05	0.0040	627
	Wood Chips	0	1.17	2.5E-06	0.092	1.26
Liquid/Gas	Ethanol from Sugarcane	253	61.0	1.25	0	315
	Ethanol from Wood	0	1.27	2.8E-05	0	1.27
	Biogas from Dung	0	14.6	0	0	14.6
	LPG	234	18.3	23.8	0	276

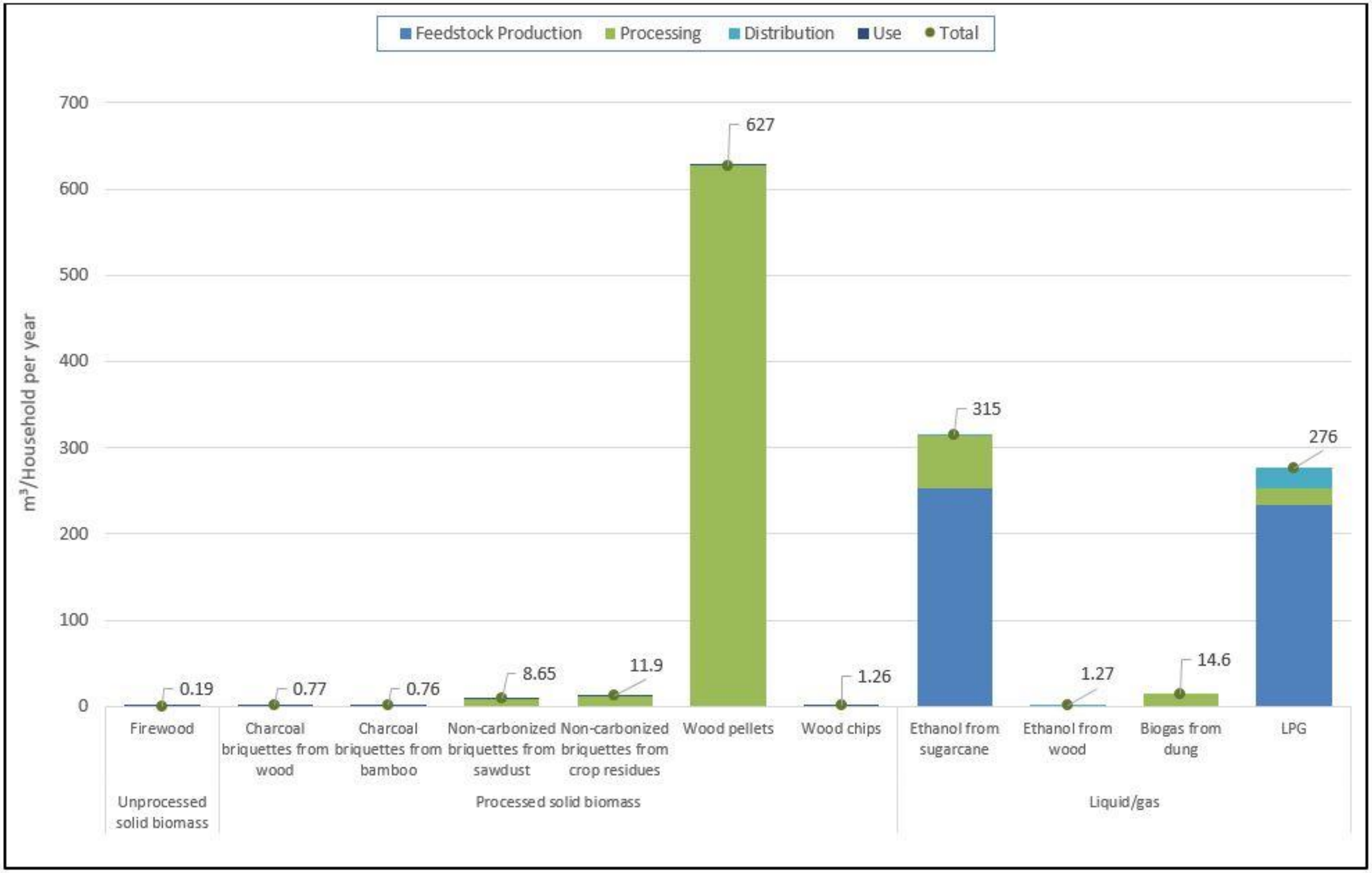


Figure A-80. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (Kenya)

To produce, distribute and use cooking fuels by a single household per year

A.8.2.8 Terrestrial Acidification Potential

Table A-88 and Figure A-81 show the terrestrial acidification potential impact results for fuels in Kenya by life cycle stage. Terrestrial acidification quantifies the acidifying effect of substances on their environment. Important contributing emissions include SO_2, NO_x, and NH_3. Firewood and charcoal briquettes from sawdust have the highest overall acidification impacts. The main contributing emissions leading to acidification potential for the traditional fuels are SO_x and NO_x. Ethanol contains no sulfur, so there are no sulfur dioxide emissions, a main cause of acidification, for the ethanol cookstove use stage. However, there are notable emissions leading to acidification during cultivation and processing of the cane to molasses and then to ethanol. A similar magnitude of acidification impacts are seen for LPG as for ethanol. Distribution acidification impacts in Kenya are highest for transportation of the carbonized and non-carbonized briquettes since a greater mass of input fuel for the solid biomass is required to be transported a longer distance given the proximity of end users to forests in Kenya (Appendix B provides detailed discussions of the model's transportation parameters). The lowest overall acidification impacts are seen for biogas. Because land applied digested sludge from biogas production is used by another product system, it is considered to be outside the system boundaries for this analysis; however, it is possible that this land applied digested sludge could lead to emissions of ammonia, an acidifying substance.

Table A-88 Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (Kenya)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	2.35	2.35
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.020	0.23	0.47	0.72
	Charcoal Briquettes from Bamboo	0	0.019	0.23	0.47	0.72
	Non-Carbonized Briquettes from Sawdust	0	0.016	0.66	1.74	2.41
	Non-Carbonized Briquettes from Crop Residues	0	0.0047	1.2E-04	0.97	0.98
	Wood Pellets	0	0.26	0.13	0.15	0.54
	Wood Chips	0	0.029	0.0033	1.13	1.16
Liquid/Gas	Ethanol from Sugarcane	1.40	0.69	0.15	0	2.24
	Ethanol from Wood	0	0.33	0.037	0	0.37
	Biogas from Dung	0	0	0	0.070	0.070
	LPG	0.71	1.11	0.038	0.40	2.26

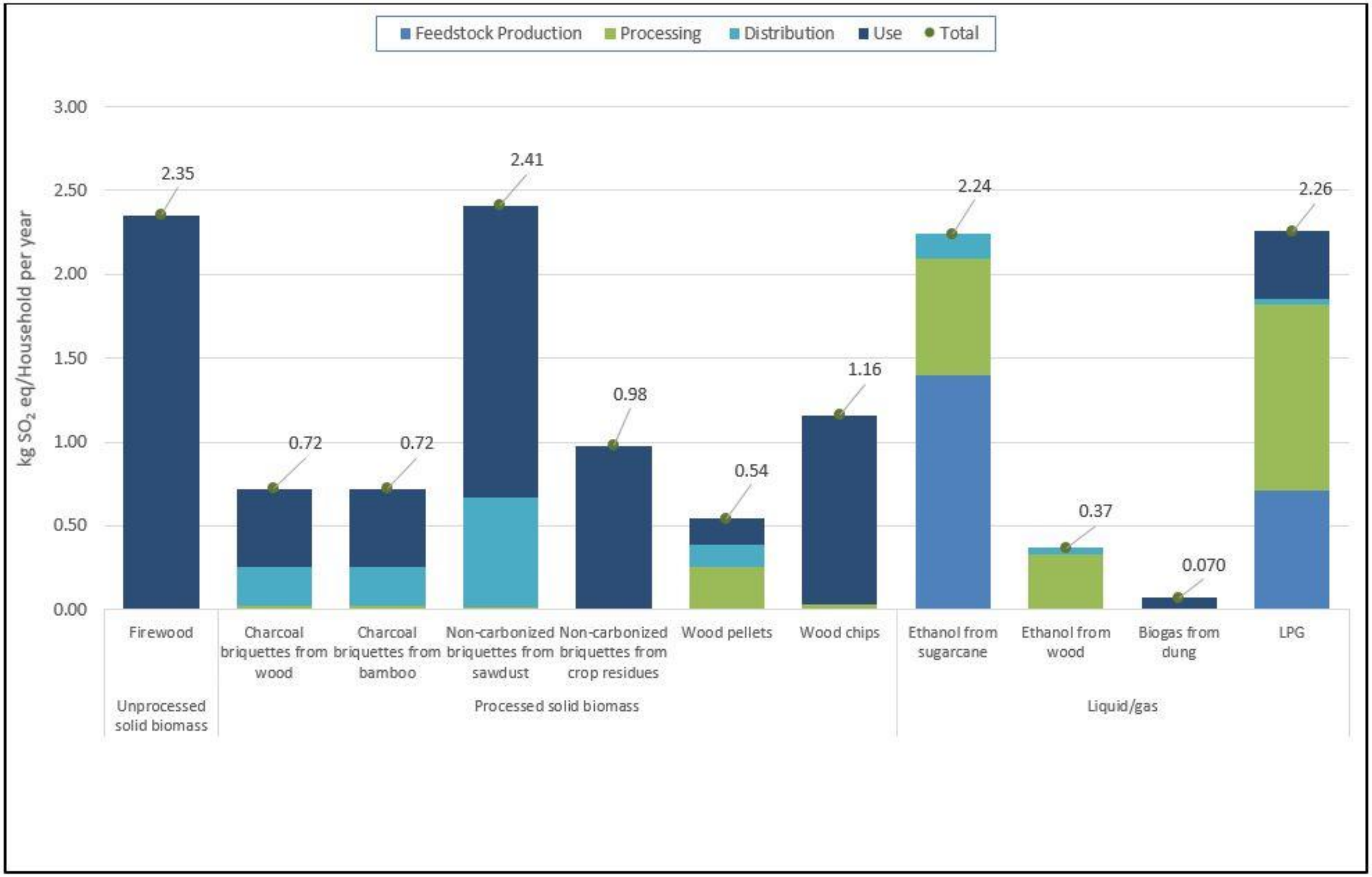


Figure A-81. Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (Kenya)
To produce, distribute and use cooking fuels by a single household per year

A.8.2.9 Freshwater Eutrophication Potential

Table A-89 and Figure A-82 provide the freshwater eutrophication potential impact results for fuels in Kenya by life cycle stage. Eutrophication assesses the impacts from excessive load of macro-nutrients to the environment and eventual deposition in freshwater, which can result in algal blooms, oxygen depletion, and fish kills. Pollutants contributing to this category are all P based (e.g. phosphate, phosphoric acid, phosphorus). Firewood results in the highest eutrophication potential impacts. This is due to the larger ash quantity produced from Firewood compared to all other fuels. The ash from the firewood, which contains phosphorus is assumed to be land applied, which leads to soil emissions and eventual runoff into freshwater. Ash production is also the reason other processed biomass fuels have a relatively high eutrophication impact, with wood combustion at the charcoal kiln leading to the relatively high eutrophication of charcoal briquettes. The non-carbonized processed biomass fuels have slightly lower eutrophication potential impacts than traditional unprocessed biomass fuels. Because processed biomass burns more efficiently than unprocessed biomass, less fuel must be burned, leading to an overall lower quantity of ash produced. While impacts are comparably smaller for ethanol, there are some eutrophication impacts occurring from use of phosphorus based fertilizer in sugarcane production. There are no eutrophication impacts associated with biogas. Application of the digested sludge from the biogas system would likely lead to some eutrophication impacts, but utilization of this useful co-product is outside the system boundaries of this study. The digested sludge impacts are allocated to the product system it serves (i.e. nutrients for crop production). Impacts from fossil based fuels and biomass pellets are minimal compared to the traditional fuels.

Table A-89. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (Kenya)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	0.62	0.62
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.27	1.9E-07	0.045	0.31
	Charcoal Briquettes from Bamboo	0	0.26	1.9E-07	0.045	0.31
	Non-Carbonized Briquettes from Sawdust	0	0.0029	5.6E-07	0.39	0.39
	Non-Carbonized Briquettes from Crop Residues	0	2.9E-05	1.0E-10	0.30	0.30
	Wood Pellets	0	0.0018	1.1E-07	0.013	0.015
	Wood Chips	0	1.7E-04	2.8E-09	0.30	0.30
Liquid/Gas	Ethanol from Sugarcane	0.15	0.0097	1.8E-04	4.9E-06	0.16
	Ethanol from Wood	0	1.0E-05	3.2E-08	4.9E-06	1.5E-05
	Biogas from Dung	0	0	0	0	0
	LPG	0.033	0.0025	4.6E-05	0	0.036

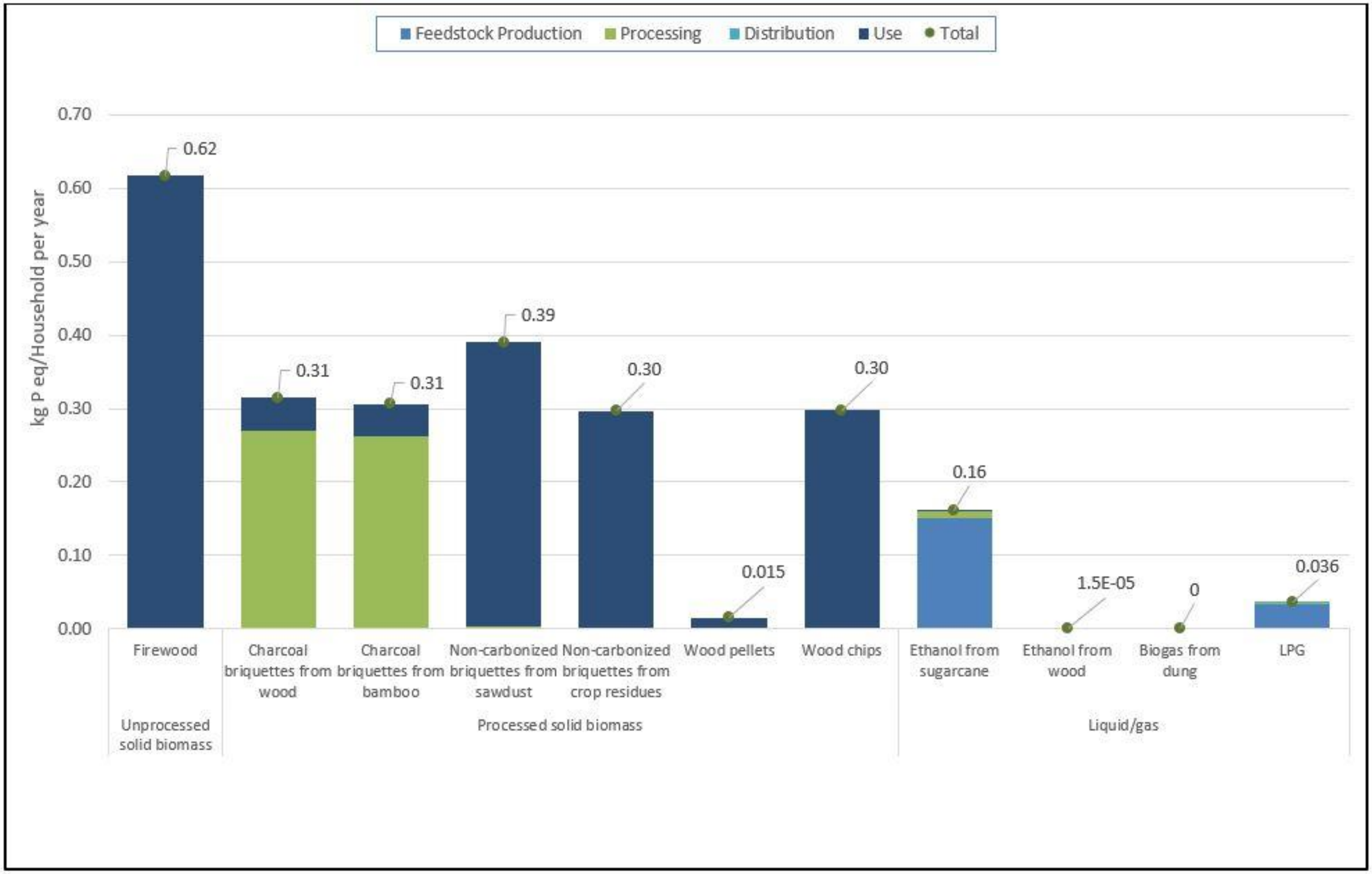


Figure A-82. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (Kenya)

To produce, distribute and use cooking fuels by a single household per year

A.8.2.10 Photochemical Oxidant Formation Potential

Table A-90 and Figure A-83 present the photochemical oxidant formation potential impact results for fuels in Kenya by life cycle stage. The photochemical oxidant formation (i.e. smog formation) results are an indicator of the potential for formation of reactive substances that cause harm to human health and vegetation. Results are characterized here to kg of non-methane volatile organic compounds (NMVOC) eq. Some key emissions for cookstove fuel systems that contribute to photochemical oxidant formation include carbon monoxide, methane, nitrogen oxides, NMVOCs, and sulfur dioxide. Firewood and charcoal briquettes lead to the greatest photochemical formation impacts, followed by processed biomass fuels. For charcoal briquettes, impacts are dominated by the fuel processing stage (carbonization in a kiln). Photochemical oxidant formation impacts are relatively small for the liquid fuels, processed non-carbonized biomass and biogas.

Table A-90. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (Kenya)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	**Processing**	**Distribution**	**Use**	**Total**
Unprocessed Solid Biomass	Firewood	0	0	0	106	106
Processed Solid Biomass	Charcoal Briquettes from Wood	0	107	0.40	22.0	129
	Charcoal Briquettes from Bamboo	0	106	0.40	22.0	129
	Non-Carbonized Briquettes from Sawdust	0	0.58	1.12	78.4	80.1
	Non-Carbonized Briquettes from Crop Residues	0	0.0032	2.0E-04	13.9	13.9
	Wood Pellets	0	0.41	6.0E-06	0.47	0.88
	Wood Chips	0	0.049	0.0057	51.1	51.1
Liquid/Gas	Ethanol from Sugarcane	0.77	0.21	0.11	0.28	1.38
	Ethanol from Wood	0	0.57	0.064	0.28	0.92
	Biogas from Dung	0	0	0	0.37	0.37
	LPG	1.64	0.90	0.062	4.83	7.42

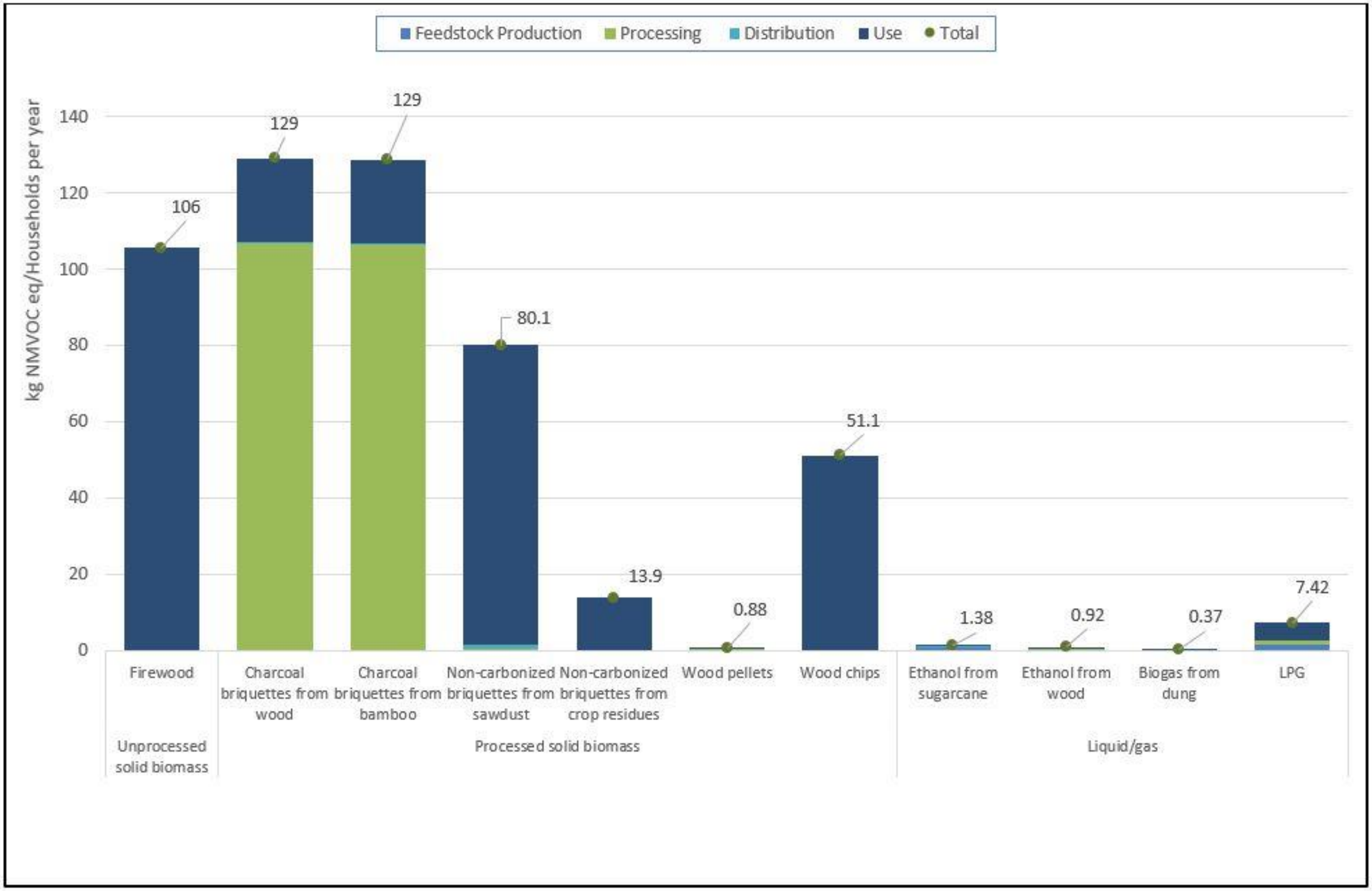


Figure A-83. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (Kenya)
To produce, distribute and use cooking fuels by a single household per year

A.8.3 Economic Indicators for Kenya

A.8.3.1 Fuel Use

Figure A-84 shows the percentage of the population in Kenya using various types of fuel as their primary cooking fuel. Biomass, which consists mainly of firewood, dominates the cooking fuels, as it is used by nearly 70 percent of the population. Firewood use is particularly dominant in rural and peri-urban areas (those between urban and rural areas) and among those with low incomes.[494,495,496]About 13 percent of the population use charcoal, another 13 percent use kerosene, and less than one percent use electricity or other fuels.[497] Of these fuels, charcoal and electricity are more commonly used in urban areas than in rural areas.[498] About 3.5 percent of the population uses LPG.[499]

Other fuels are available from small enterprises, but these are not widely used at this time. For example, sugarcane-based ethanol is produced in Kenya on a limited basis[500] and is sold as a cooking fuel by small enterprises in both liquid and gel form.[501] Some small enterprises are also selling both carbonized and non-carbonized wood briquettes, but the latter are used more for industrial purposes than household cooking.[502] Biogas is used where households have enough livestock to feed the digester, but not many households have sufficient livestock to support a digester.[503] Ethanol from sawdust and wood chips are not believed to be used in Kenya.[504] As population increases and forest area is declining, the use of firewood and wood charcoal is increasingly unsustainable.[505] As a result, Kenya's fuel use pattern will likely shift away from wood toward some of the non-traditional fuels.

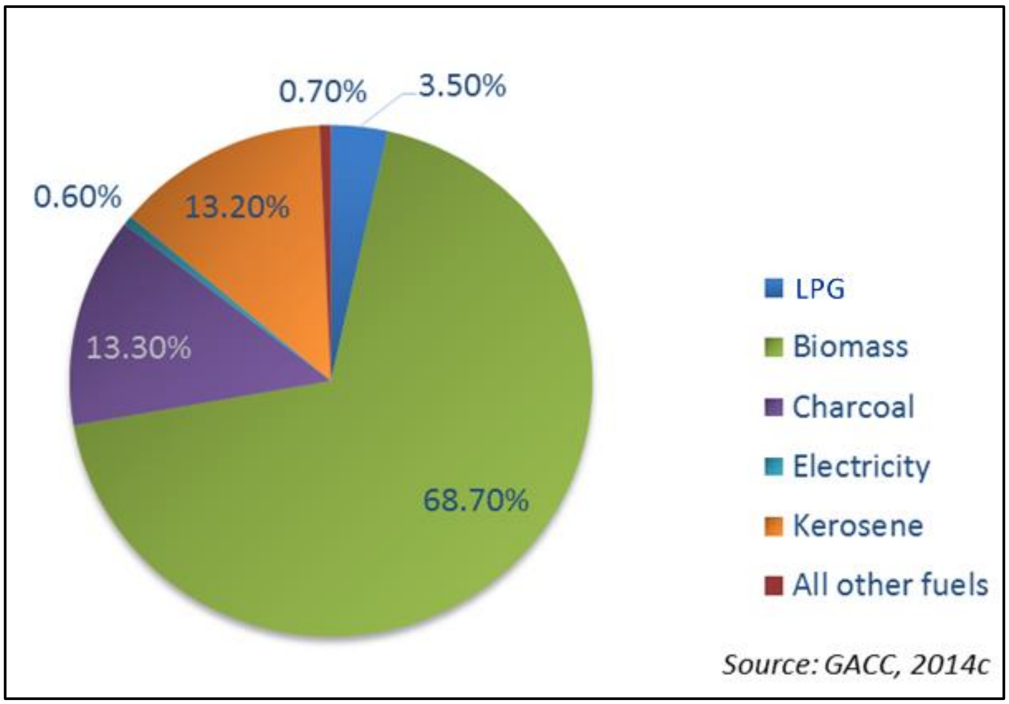


Figure A-84. Current Cooking Fuel Mix in Kenya

A.8.3.2 Fuel Imports, Exports, Production, and Demand in Kenya

Table A-91 shows the levels of imports, exports, production, and demand (assumed to be equal to current consumption) of several fuels in Kenya. The data on total and household demand do not differentiate between fuel use for cooking and fuel use for other purposes such as heating.

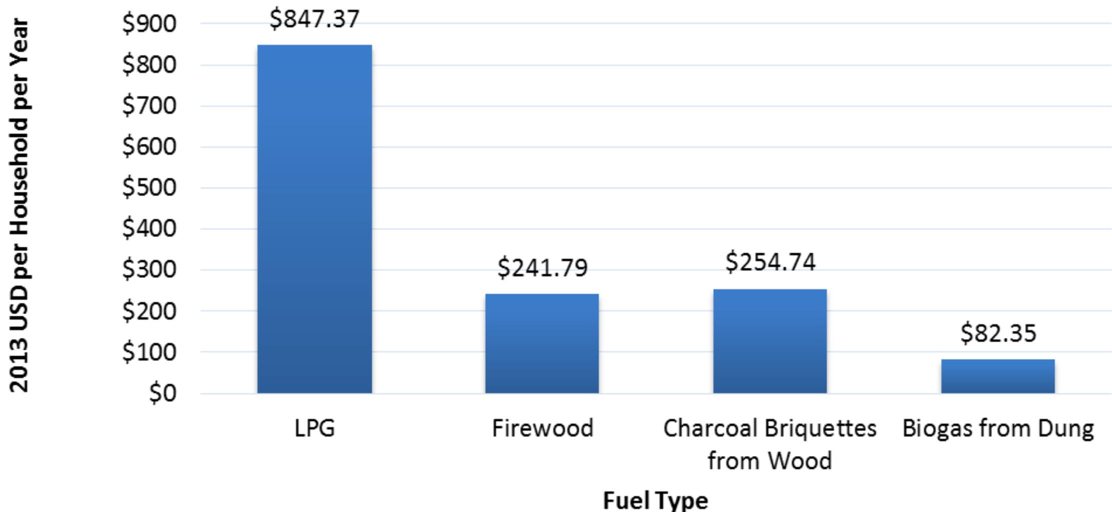
LPG is not widely used in Kenya, with 91,000 tonnes consumed, about two thirds of which is imported. Of this demand, about 31 percent is consumed by households.[506] Kenya produces 26.4 million tonnes of firewood per year[507] and was projected to be consuming 40.9 million tonnes of firewood in 2015.[508] About 17,700 tonnes of wood charcoal were estimated to be produced, with all of the charcoal consumed by households.[509] This is by far the lowest amount of charcoal reported for any of the countries in this study and might indicate the existence of informal charcoal markets that are not captured in national statistics.

Table A-91. Fuel Imports, Exports, Production, and Demand in Kenya (Tonnes per Year)

Fuel	Imports	Exports	Production	Demand		Sources
				Total	Household	
LPG	63,000	No data	28,000	91,000	37,000	UNSD, 2011
Firewood	No data	No data	26,400,000	40,941,673	No data	FAO, 2014 Ngusale et al., 2014
Charcoal Briquettes	No data	No data	17,700	17,700	17,700	UNSD, 2011

A.8.3.3 Fuel Cost in Kenya

Figure A-85 shows the price per household per year for the cooking fuels in Kenya for which cost data are available. LPG is by far the most expensive fuel, at close to $850 per household per year.[510,511,512,513] It is difficult for poorer households to afford LPG because it must be purchased in large cylinders, which are expensive. If LPG were available in smaller cylinders, the overall cost per household per year would likely not change dramatically but use may increase, since it would be more affordable for poorer households to purchase smaller amounts at a time. Purchased firewood[514,515,516,517] and wood charcoal[518,519,520] both cost about $250 per household per year. The annualized cost of a biogas digester makes biogas the least expensive of the fuels with available cost data, at about $82 per household per year.[521] In rural areas, firewood can be collected at essentially no cost.[522]



Note: No data available for fuel types not included.

Sources: GVEP International, 2012a; GVEP International, 2012d; EAC, 2006; Matthews & Zeissig, 2011; EnDev, 2012; Djédjé, et al., 2009; Ngusale, et al., 2014; Versol, 2015

Figure A-85. Fuel Cost Indicator for Cooking Fuels in Kenya

A.8.4 Social Indicators for Kenya

A.8.4.1 Government Policies/Programs

Although the Kenyan government is interested in, and has adopted policy positions on, cookfuel-related issues, a market assessment found that "opportunities exist to develop stronger, more coordinated interventions."[523] One promising step is the Ministries of Revenue, Trade, and Energy's institution of a tax structure for sugarcane-based ethanol as fuel for domestic use. Although the new legislation is aimed primarily at improving the competitiveness of Kenya's sugar industry, the new tax structure was supported by FAO's Policy Innovation Systems for Clean Energy Security (PISCES) and indicates the potential for improving Kenya's alternative fuel landscape, especially when government, industry, and advocacy efforts are aligned.[524] Other policies for which data are available pertain to LPG, charcoal briquettes from wood, biogas from crop residue, and clean cookstoves in general (which have been promoted through the Ministry of Energy and Agriculture, and—in the case of one project—subsidized through carbon financing).[525]

Although specific elements of Kenya's LPG policies are not available, the legislation is largely aimed at equipment standardization,[526] which would likely improve safety issues. There is also a lack of data surrounding biogas produced from crop residues, although GVEP International notes that the Kenyan Government is promoting its use for cooking under the National Biogas Program, which aimed to install 8,000 digesters by 2013.[527] With respect to charcoal, poor design and implementation of policies has inhibited the development of trade in Kenya;[528] for example, national policies are unclear on which ministries regulate briquettes,[529] studies indicate that requisite payments by producers (in the form of "unofficial tax levying" and "private taxes") currently account for 20 to 30 percent of the final price paid by charcoal customers, and unregulated charcoal trade results in landowners receiving very little compensation for the feedstock wood produced on their land.[530] One study investigating the distribution of benefits from charcoal made in Narok and sold in Nairobi found that police bribes accounted for a 2 percent markup in wood-based charcoal prices, and that other expenses such as broker fees, local government permits, and vendor costs represented equal or larger shares of wood-based charcoal profits than those received by feedstock owners.[531] Moreover, in the absence of country-specific standards for briquettes,[532] some Kenyan producers have unofficially adopted South African standards to certify the quality of their goods.[533] A final government barrier to the development of the charcoal industry is the requirement that the certification cost of any retailed product will be borne by the producer.[534]

On the other hand, some Kenyan policies support the wood-based charcoal industry. For example, funds are available to conduct National Biomass Energy Strategies and, more generally, the government recently reaffirmed its commitment to sustainable energy and exploring future energy options.[535] On the whole, the Kenyan government's commitment to renewable energy development—including explicit reference to biomass energy sources such as briquettes in its 2010 constitution—"is bound to affect the [wood-based charcoal] briquette sector positively."[536]

A.8.4.2 Supply & Access Challenges

Although modern fuels such as kerosene and LPG are relatively easy to access in urban areas,[537] wood-based cookfuels are the most reliably acquired throughout Kenya. The most commonly used cooking fuel, firewood, is gathered freely in rural and periurban communities[538] by 60 percent and 29 percent of consumers, respectively,[539] and the wood-based charcoal briquette supply chain is considered very reliable (relative to electricity supply).[540] Forest cover, however, has been reduced to between two and six percent of total land area, and market assessments suggest deforestation due to logging will increasingly threaten Kenya's economy, water supply, and ecosystems.[541] Although currently available data do not provide insight into the impact Kenya's 0.5 percent deforestation rate[542] is likely to have on agroforestry and the availability of wood-based fuels, the emergence of alternatives suggests the anticipation of future constraints. For example, small-scale production capacity has recently been established for ethanol from sugarcane, charcoal briquettes from bamboo, and non-carbonized briquettes from rice husks.[543] Details on the reliability of acquiring these nascent fuels are not yet available.

A.8.4.3 Distribution & Adoption Challenges

Two key challenges facing the promotion of the target fuels in Kenya are a lack of awareness regarding the costs and benefits of alternative fuels[544, 545] and affordability issues. Lack of awareness sometimes manifests literally with, for example, some consumers not realizing alternatives to traditional fuels such as charcoal briquettes exist.[546] More often, however, the need to promote awareness pertains to consumers with the knowledge of and ability to pay for nontraditional fuels,[547] but perhaps without a full understanding of the benefits of adoption.

Regarding cost, without incentives or creditors to enable communities to construct improved kilns for charcoal briquette production, converting firewood to charcoal often remains cost-prohibitive.[548] Relatedly, the high upfront costs associated with biogas[549] and LPG[550] limits the ability of poorer, often rural, communities to adopt these fuels. Another issue contributing to the high cost of LPG in particular is the prevalence of middlemen in the supply chain. Each middleman adds their markup and increases the price to the end user.[551] The Pima Gas system, developed by Premier Gas, illustrates the willingness of the Kenyan alternative fuel market to accept more affordable options. As opposed to traditional (3 to 13kg) LPG cylinders, Premier Gas developed a 1 kg cylinder that is both cheaper at the outset and accepts partial refills. The system has been a success, with 15 mobile Pima units in Nairobi and the company intends to install 1,000 more.[552]

With respect to the distribution of any nontraditional fuel in Kenya, packaging is a critical consideration. Although the issues of packaging options and cost are typically associated with more expensive liquid and gaseous fuels (as with the Pima Gas example above), even fuels that are traditionally more affordable become cost-prohibitive when only available in large quantities. That is, any enterprise selling cookfuels in small quantities stands to benefit from a broader consumer base.[553] For example, carbonized briquettes from wood are relatively expensive, but because they are available in small packages with one to two days' worth of fuel, they are able to maintain some market share.[554]

Another barrier to the adoption of LPG in Kenya is the poor quality of the country's cylinder supply and the associated lack of information regarding who owns, refills, and maintains the cylinders.[555] Other challenges include the potential need for trainings on how to cook over nontraditional fuels such as wood chips. Even when target fuels are available, cultural traditions, such as using only charcoal to prepare special dishes, may inhibit the wide-scale uptake of other cookfuels.[556]

A study on the wood-based charcoal sector offers insights into challenges producers face when trying to scale up their operations. Some of these challenges apply specifically to briquettes, but others can apply to any alternative fuel trying to gain market share. Primary barriers include:

- Technological Challenges – limited technical capacity, limited access to spare parts, lack of localized technologies due to poor investment in research and development,

- Financial Challenges – high upfront costs of briquetting infrastructure, lack of experience with the briquette sector among commercial lenders, perceived credit risks among entrepreneurs, limited number of briquette developers (lack of economies of scale),

- Regulatory Challenges – uncertainty in scope of regulations, regulatory gaps, low enforcement capacities,

- Knowledge Challenges – limited entrepreneurial skills, lack of scalable business models, and

- Operational Challenges – competition from alternative sources (i.e., limited promotional/marketing work has been done to differentiate briquettes from alternative fuels), inconsistent feedstock supplies, competing feedstock and labor uses, and low quality of final product.[557]

A.8.4.4 Protection & Safety

The only fuel-specific safety concerns for which data are available in Kenya relate to the collection of firewood from remote locations. One study of the Dadaab refugee camp found that during a time period when households had most (70 percent) of their firewood supplied by the

United Nations High Commissioner for Refugees (UNHCR), sexual assaults decreased by 45.2 percent compared to assaults during periods of time spent collecting full supplies of firewood.[558] In addition to the threat of gender-based violence, women face physical risks of injuries from the repeated strain of manually gathering firewood. On average, women refugees in Kenya collect firewood 5.6 times per month, spend 7 hours per trip, and cover 9.7 kilometers. The average weight of a refugee's wood bundle per trip is 44 lbs.[559]

For purchased fuels considered in this analysis (e.g., LPG or ethanol), no safety issues during the purchase of the fuels were found within the literature. Collection of crop residues usually occurs somewhat close to the household, and no safety issues were found in the literature.

A.8.4.5 Time & Drudgery

Time spent collecting firewood in Kenya ranges between 1 and 4.5 hours per household per day depending on the proximity of forests and agricultural land.[560,561,562] Given the opportunity cost of spending such a substantial amount of time gathering fuel, any alternative to the manual collection of wood could have a meaningful social impact. For example, one study found that a partial switch to LPG resulted in net savings of 64 hours per household per year in fuel collection time.[563] Moreover, substantial time spent cooking over traditional fuels, primarily by women, greatly diminishes opportunities for other activities such as farming or the development of small enterprises.[564] For example, a study of 220 women found that time gained from faster cooking was used for farming, earning income, girls' education, and participation in community life.[565] Evidence from one study found a significant incremental benefit in time savings—961 hours per household per year—when cooking over LPG as opposed to firewood.[566] A large driver of cooking time savings, however, came from using LPG to cook quick foods or beverages (such as brewing tea).[567]

A.8.4.6 Income Earning Opportunities

Given the newness of the feedstock-fuel combinations in the present study, limited information regarding the income earning opportunities associated with specific cookfuels is available. Evidence suggests that even though sugarcane-based ethanol is produced in Kenya, income earning opportunities are limited by the fact that it is both heavily taxed and must be transported to Tanzania for processing.[568] For wood-based non-carbonized briquettes, manufacturing is not yet taking place at a large scale, so income earning opportunities, for the most part, are limited to the hiring of farmhands to help with feedstock production.[569] Wood-based charcoal briquettes, on the other hand, contribute between $450 million and $1.6 billion to Kenya's economy annually, suggesting a substantial value chain.[570] One study found that monthly incomes from charcoal briquette sales were as high as $1,771 during the dry season and $2,240 during the wet season.[571] On the other hand, an estimated 700,000 people are employed in the *informal* charcoal industry, presumably comprising small-scale operations not included in national employment statistics, GDP calculations, etc., making it difficult to project income earning opportunities.[572] Although biogas systems for use with animal dung have some use at the household level, it is not considered a strong market for commercialization.[573]

Evidence from a market assessment suggests that income earning opportunities exist in the LPG industry.[574] Specifically, there is strong consumer demand for LPG and other modern fuels, but would-be users tend to have trouble affording expensive equipment and large quantities of fuel upfront. Therefore, there are strong market opportunities for innovative enterprises able to lower one-time costs of liquid fuel stoves and distribute smaller cylinders that would lower refill costs.[575]

A.8.4.7 Opportunities for Women Along the Value Chain

According to the Global Alliance for Clean Cookstoves 2013 Results Report, the clean cookstove industry in Kenya currently has 959 employees (46 percent of whom are women) and 1,675 microentrepreneurs (47 percent of whom are women).[576] Although the majority (60 to 70 percent) of workers in the firewood industry are male,[577] community-based organizations making charcoal briquettes from wood present a substantial opportunity for women. These enterprises represent 50 percent of the briquette-making enterprises in Kenya and have a focus on hiring children, as well.[578] Market segmentation studies indicate that producers who make briquettes by hand tend to have the highest proportions of female employees.[579] For operations relying on technologies less suited for female workers (such as manual presses, which can be tiring to operate), there are still sometimes opportunities for women as record keepers, counters, and packers.[580] Evidence suggests that there are opportunities for women in the retailing of charcoal even outside of such community-based organizations.[581] In many cases, the income women generate through selling charcoal is used for livelihood needs such as food, health, school fees, and rent.[582] Some business models for women-owned enterprises even involve a "special focus on utilizing the trading and networking skills of women in low income areas to sell briquettes."[583] In general—and particularly in rural communities—however, labor tends to organize along patriarchal lines, with men dominating public sectors and formal markets and women primarily tasked with domestic responsibilities.[584]

A.9 Detailed Results for Uganda

A.9.1 Overview of Uganda

Uganda is Eastern Africa's fourth largest country, with a 2015 population of 40.1 million. [585] As in most of the Alliance's focus countries, a large portion of the population uses unprocessed biomass to cook. Eighty-seven percent of the population lives in rural areas and 13 percent in urban areas.[586] As of 2012, 38 percent of the population in the country was below the international poverty line of $1.25 per capita per day.[587] One-third of households are headed by women.

Adequate supply of resources to sustainably support current or increasing levels of firewood use is an important consideration. Uganda has had more than 2 percent decrease in forest land per year over recent years,[588] and only 15 to 26 percent of Uganda's land area is covered by forest.[589] Nearly 22 percent of the rural population live in areas with woody biomass shortfalls.[590]

Rural households mostly cook on three-stone fires, often in enclosed spaces.[591] Households across Uganda generally eat similar foods and have the same cooking habits (boiling and simmering).[592] Cookstoves are also used to boil water for tea and porridge.

The following sections of this appendix address the environmental, economic, and social considerations related to cooking fuels and stoves for Uganda in greater detail.

A.9.2 Environmental Indicators for Uganda

This section covers the detailed Uganda LCA results for the ten environmental indicators assessed for each fuel. The stove thermal efficiency by fuel and the fuel heating values employed in this study to calculate the LCA results are provided in Table A-92 and Table A-93, respectively. The remainder of this section presents results for each environmental indicator.

Table A-92. Stove Thermal Efficiency Applied by Fuel for Uganda

Fuel Type	Stove Thermal Efficiency	Sources
Firewood	15.0%	GACC, 2010
Charcoal Briquettes from Wood	18.0%	Afrane & Ntiamoah, 2011
Charcoal Briquettes from Bamboo	18.0%	Afrane & Ntiamoah, 2011
Non-Carbonized Briquettes from Sawdust	20.3%	GACC, 2015a Urban Uganda, 2015
Non-Carbonized Briquettes from Crop Residues	31.0%	GACC, 2015a
Wood Pellets	53.0%	Jetter et al., 2012
Wood Chips	31.0%	GACC, 2015a
Ethanol from Sugarcane	53.0%	Aprovecho Research Center, 2009
Ethanol from Wood	53.0%	Aprovecho Research Center, 2009
Biogas from Dung	55.0%	Afrane & Ntiamoah, 2011
LPG	57.0%	Afrane & Ntiamoah, 2011

Table A-93. Fuel Heating Values for Uganda

Fuel Type	HHV (MJ/kg)	Sources
Firewood	16.0	GACC, 2010
Charcoal Briquettes from Wood	25.72	Afrane & Ntiamoah, 2011
Charcoal Briquettes from Bamboo	25.72	Afrane & Ntiamoah, 2011
Non-Carbonized Briquettes from Sawdust	20.1	Ferguson, 2012
Non-Carbonized Briquettes from Crop Residues	17.7	Simonyan & Fasina, 2013 FAO, 2015 Duku et al., 2011 Phyllis2, 2015
Wood Pellets	17.94	Singh et al., 2014 Jetter et al., 2012
Wood Chips	16.0	GACC, 2010
Ethanol from Sugarcane	28.3	Aprovecho Research Center, 2009
Ethanol from Wood	28.3	Aprovecho Research Center, 2009
Biogas from Dung	17.71	Afrane & Ntiamoah, 2011
LPG	45.84	Afrane & Ntiamoah, 2011

A.9.2.1 Total Energy Demand

Table A-94 and Figure A-86 display the total energy demand impact results for fuels in Uganda by life cycle stage. Total energy demand sources consist of non-renewable fuels (natural gas, petroleum, coal, and nuclear) and "renewable" fuels (e.g. biomass, hydro). Energy demand tracks all energy inputs across the life cycle of the fuel, with energy impacts shown at the point of use of the relevant fuel.

The total energy demand results are largely a function of the fuel heating value and thermal efficiency of the fuel and stove combination (Table A-92 and Table A-93). Stoves with higher efficiencies (e.g., LPG, biogas, ethanol, and biomass pellets) have a lower total energy demand overall, because more of the heating value of the fuel is converted into useful cooking energy and therefore less fuel must be produced, transported, and burned to deliver the same amount of cooking energy.

A number of observations can be made regarding energy results for the various types of fuels. For sugarcane ethanol, the feedstock energy results include not only the energy value of the sugar that is converted to ethanol but also the energy content of the bagasse, which provides the majority of energy used to process the sugarcane to ethanol. A co-benefit of ethanol production is the production of electricity, which may be exported. As discussed in the Appendix B methodology, this model employs the cut-off allocation methodology; therefore, a credit is not given here to the sugarcane or wood ethanol for exported electricity, so the energy demand impacts for ethanol should be considered as the upper bounds for these fuel types.

For wood fuels, the wood pellets and wood chips have a lower total energy demand than traditional firewood. Wood chips and wood pellets typically have a lower moisture content, greater energy content, and greater surface area than the traditional solid biomass, which allows the fuel to combust more efficiently. It is also more common to see improved cookstoves, which have higher stove thermal efficiencies, used in combination with the wood chips and wood pellets in Uganda.

For briquettes, the energy demand impact for the carbonized briquettes from wood and bamboo is relatively higher compared to other fuels due to the lower stove efficiencies for metal charcoal briquette stoves in Uganda and the charcoal kiln energy impacts. That is, additional energy is consumed when burning firewood at the kiln to produce charcoal prior to charcoal utilization in a cookstove. Similarly, in processing the commercially made non-carbonized sawdust briquettes (3% of sawdust briquettes are assumed to be produced commercially in Uganda), sawdust is combusted to remove the moisture content of the briquettes, which contributes to the relatively higher total energy demand of the sawdust briquettes compared to other non-carbonized processed biomass fuels. The remaining 97% of sawdust briquettes are modeled as pressed manually and dried naturally to 10% moisture content. This requires 1.5 kg wood input to each 1 kg briquette, assuming a 40% moisture content of the original greenwood.[173]

Overall, liquid and gas fuels as well as processed solid biomass fuels not requiring additional combustion of solid fuel for processing (e.g., wood pellets) lead to the lowest overall total energy demand impacts.

Table A-94. Total Energy Demand (MJ) for Cooking Fuel Types (Uganda)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total
		Feedstock Production	Processing	Distribution	Use	
Unprocessed solid biomass	Firewood	0	0	0	39,705	39,705
Processed solid biomass	Charcoal briquettes from wood	0	45,042	0.032	33,070	78,111
	Charcoal briquettes from bamboo	0	43,788	0.032	33,070	76,858
	Non-carbonized briquettes from sawdust	0	15,888	0.74	29,323	45,211
	Non-carbonized briquettes from crop residues	0	28.1	4.9E-04	21,588	21,616
	Wood pellets	0	3,544	0.41	11,231	14,775
	Wood chips	0	87.7	0.014	19,202	19,289
Liquid/gas	Ethanol from sugarcane	581	26,802	117	11,231	38,731
	Ethanol from wood	0	1,380	0.12	11,231	12,611
	Biogas from dung	0	0	0	10,540	10,540
	LPG	3,171	25,469	41.8	10,443	39,125

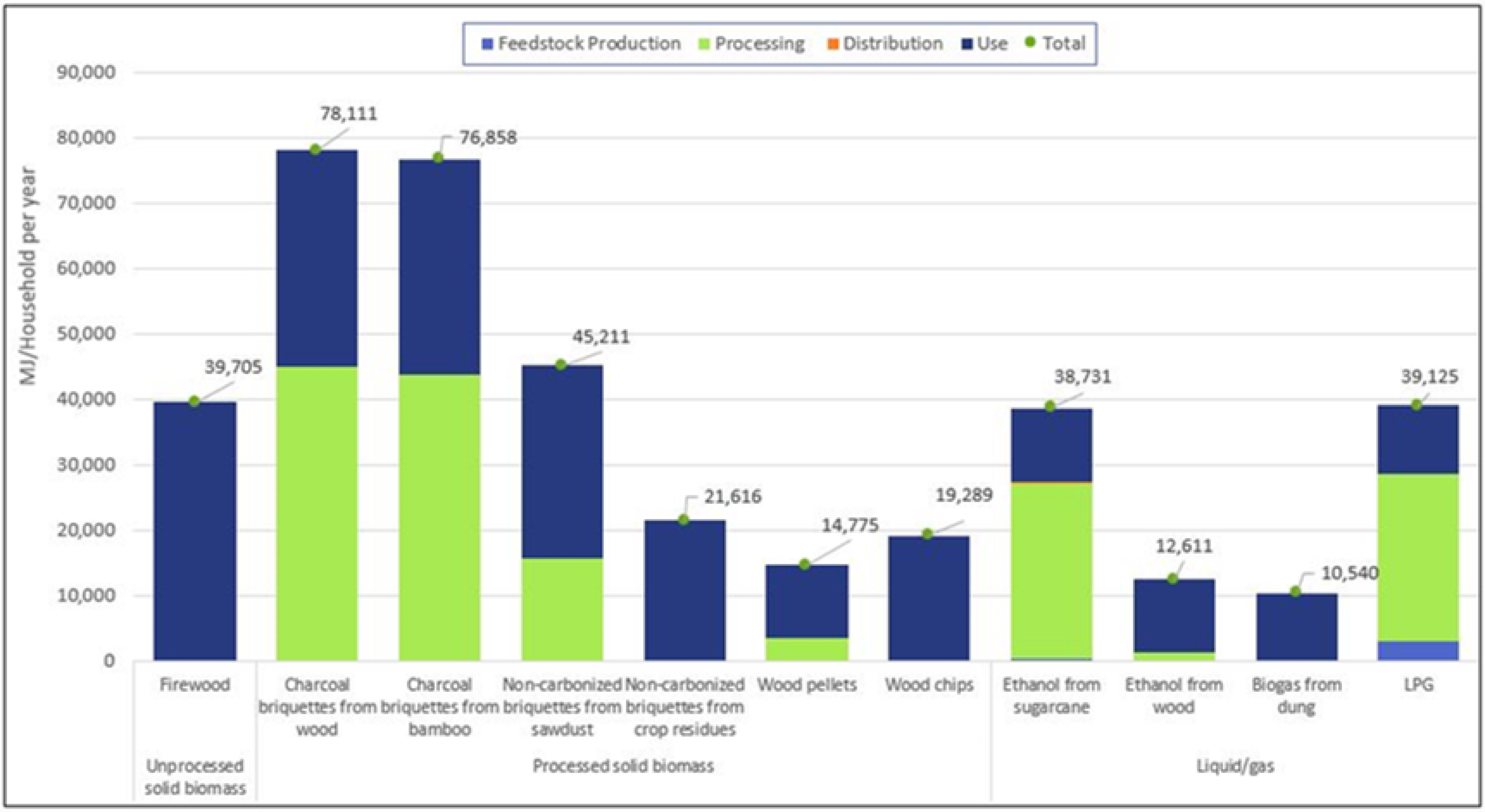


Figure A- 86. Total Energy Demand (MJ) for Cooking Fuel Types (Uganda)
To produce, distribute and use cooking fuels by a single household per year

A.9.2.2 Net Energy Demand

Table A-95 and Figure A-87 illustrate the net energy demand impact results for fuels in Uganda by life cycle stage. Net energy demand is calculated in the same way as total energy demand, with the final energy delivered to the cooking pot deducted from the results. The net energy indicator is, therefore, the additional energy required for the life cycle of the cookstove fuel beyond what is delivered to the consumer for cooking purposes. For Uganda, 16.3 MJ of cooking energy are consumed per household per day, which equates to 5,953 MJ per household per year.[593, 594] Utilization of firewood consumes approximately seven times more energy than is provided to the pot, as listed in the last column of Table A-95. Similar levels of net energy demand are seen for non-carbonized briquettes from sawdust, and LPG. The lowest overall net energy demand is calculated for non-carbonized briquettes from crop residues, wood pellets, wood chips, ethanol, and biogas from dung. Production, processing, distribution, and use of these less energy intensive fuels uses 0.77 to 2.63 times the amount of energy delivered to the pot. Charcoal briquettes result in the highest net energy demand due to the lower yield at the kilns in African countries as compared to countries investigated in other world regions. For Uganda, 3.2 kg of wood are required for 1 kg charcoal output at the earth mound kiln.[595] Energy impacts are also higher for petroleum refining in Africa as compared to other world regions modeled, resulting in the notable net energy demand burdens of LPG.[327]

Table A-95. Net Energy Demand (MJ) for Cooking Fuel Types (Uganda)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total	Net Energy Consumed: Delivered Energy
		Feedstock Production	Processing	Distribution	Use		
Unprocessed solid biomass	Firewood	0	0	0	33,752	33,752	5.67
Processed solid biomass	Charcoal briquettes from wood	0	45,042	0.032	27,117	72,159	12.1
	Charcoal briquettes from bamboo	0	43,788	0.032	27,117	70,905	11.9
	Non-carbonized briquettes from sawdust	0	15,888	0.74	23,370	39,259	6.60
	Non-carbonized briquettes from crop residues	0	28.1	4.9E-04	15,635	15,664	2.63
	Wood pellets	0	3,544	0.41	5,279	8,823	1.48
	Wood chips	0	87.7	0.014	13,249	13,337	2.24
Liquid/gas	Ethanol from sugarcane	581	26,802	117	5,279	32,779	5.51
	Ethanol from wood	0	1,380	0.12	5,279	6,659	1.12
	Biogas from dung	0	0	0	4,588	4,588	0.77
	LPG	3,171	25,469	41.8	4,490	33,173	5.57

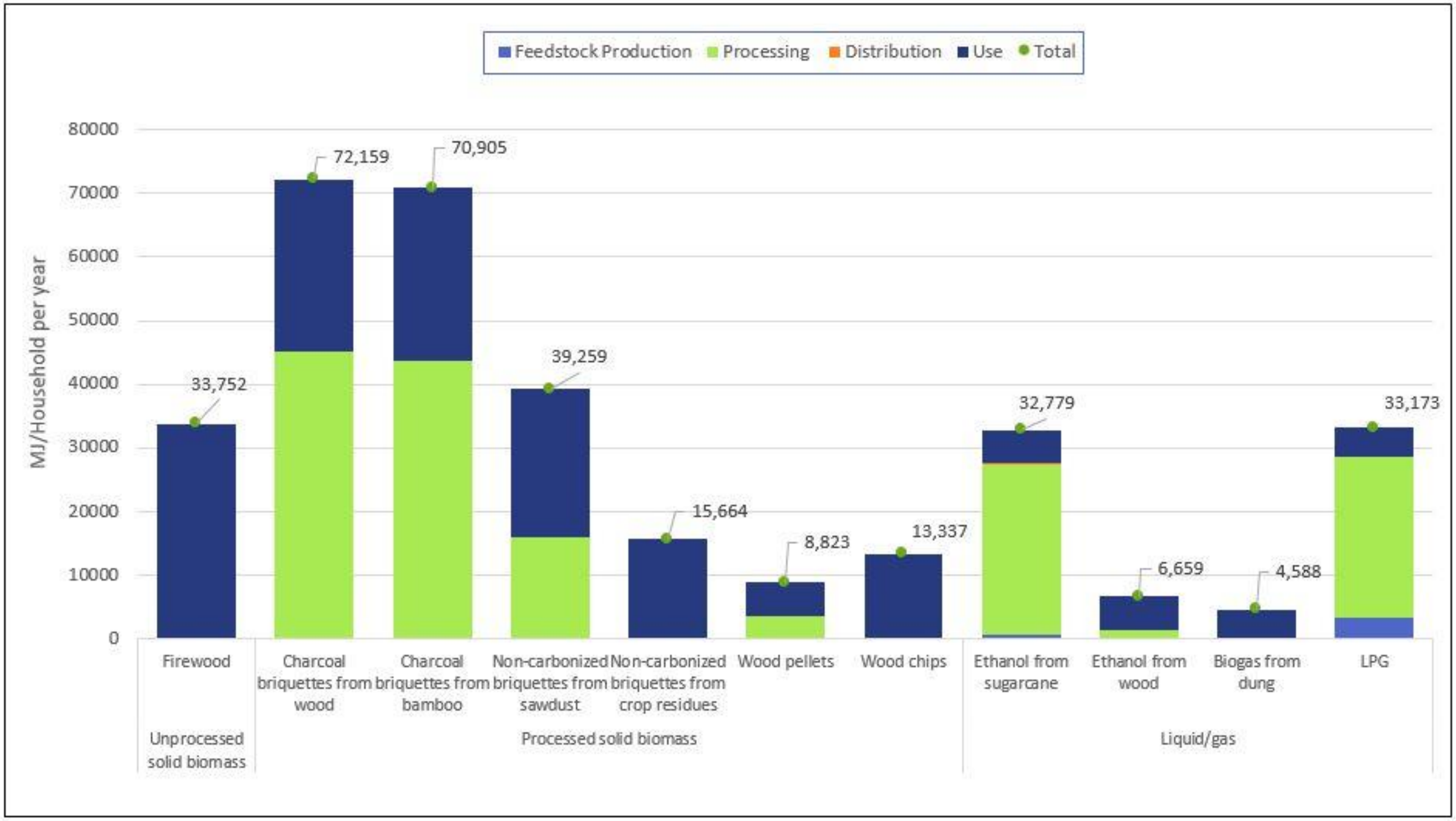


Figure A-87. Net Energy Demand (MJ) for Cooking Fuel Types (Uganda)

To produce, distribute and use cooking fuels by a single household per year

A.9.2.3 Global Climate Change Potential (100a)

Table A-96 and Figure A-88 present the GCCP impact results for fuels in Uganda by life cycle stage. The GCCP impact category represents the heat trapping capacity of greenhouse gases over a 100 year time horizon. Fossil fuel GCCP impacts are dominated by combustion emissions in the cookstove use stage.

Biogas GCCP impacts are primarily from methane leakage during the production of biogas in an anaerobic digester (1% of biogas escapes as fugitive emissions at the digester).[596] Sugarcane ethanol, crop residue briquettes, and charcoal briquettes from bamboo are derived from renewable biomass that removed CO_2 from the atmosphere during growth; therefore, the CO_2 emissions released from combustion of these fuels is considered carbon neutral, as discussed in detail in the Appendix B methodology. Impacts for these renewable fuels during the use phase are driven by nitrous oxide and methane emissions during cookstove use. Impacts associated with fertilizer production and emissions from application also play a role in the sugarcane ethanol overall impacts.

Based on the decreasing trend in forest area in Uganda, all of the wood harvested for use as cooking fuel is considered unsustainably sourced, and the combustion emissions for the non-sustainable use of wood are not considered carbon-neutral. This adjustment is also applied to other wood fuels (wood-derived charcoal briquettes, wood pellets and wood chips), but not to fuels derived from wood wastes (wood ethanol and non-carbonized briquettes from sawdust). With the cut-off modeling methodology used in this analysis, wood wastes are treated as a “free” product (all burdens are allocated to the primary wood product, e.g., lumber, which is outside the scope of this study), so emissions of biomass CO_2 for fuels derived from wood waste are treated as carbon neutral. For charcoal briquettes, GCCP impacts for carbonization of the wood in the kiln are higher in magnitude than the emissions from combustion of the charcoal briquettes in a cookstove. Charcoal kiln impacts are largely driven by the methane emissions during the carbonization process. Combustion emissions for bamboo-derived charcoal briquettes are lower than for wood-derived charcoal briquettes because bamboo is a renewable crop and all combustion emissions are considered carbon-neutral, while none of the wood combustion emissions are considered carbon-neutral, since the wood supply in Uganda is considered non-renewable based on the decreasing forest area. All GHGs associated with the production and combustion of LPG, including CO_2 emissions from cooking, are considered fossil-derived and accounted for in the GCCP impacts.

Table A-96. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (Uganda)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	4,464	4,464
Processed Solid Biomass	Charcoal Briquettes from Wood	0	3,512	54.7	3,460	7,027
	Charcoal Briquettes from Bamboo	0	1,617	54.7	528	2,200
	Non-Carbonized Briquettes from Sawdust	0	3.52	54.7	450	508
	Non-Carbonized Briquettes from Crop Residues	0	0.72	0.036	270	271
	Wood Pellets	0	50.1	30.7	2,041	2,121
	Wood Chips	0	4.95	1.04	2,164	2,170
Liquid/Gas	Ethanol from Sugarcane	475	31.5	27.7	5.69	540
	Ethanol from Wood	0	29.2	8.77	5.69	43.7
	Biogas from Dung	0	2.42	0	15.3	17.8
	LPG	259	62.9	24.2	1,661	2,007

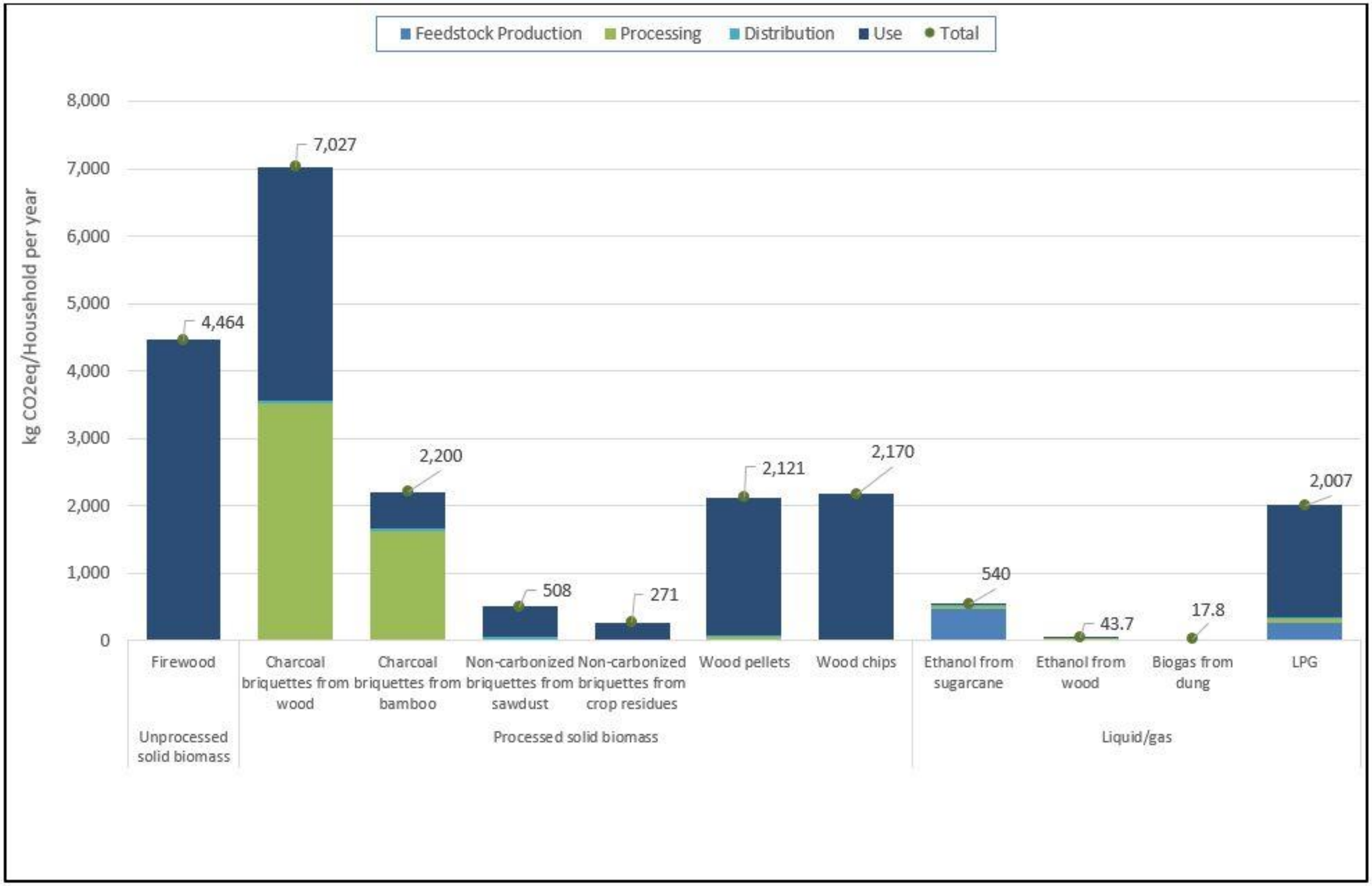


Figure A-88. Global Climate Change (100a) Potential Impacts (kg CO_2 eq) for Cooking Fuel Types (Uganda)
To produce, distribute and use cooking fuels by a single household per year

A.9.2.4 Black Carbon and Short-Lived Climate Pollutants

Table A-97 and Figure A-89 display the black carbon and short-lived climate pollutants impact results for fuels in Uganda by life cycle stage. Black carbon (BC) is formed by incomplete combustion of fossil and bio-based fuels. BC is the carbon component of particulate matter (PM) with aerodynamic diameter less than or equal to 2.5 microns (PM2.5). This is the size of PM that most strongly absorbs light and thus has potential radiative forcing effects (i.e., potential to contribute to global warming). Potential climate forcing impacts resulting from BC emissions include direct, albedo (i.e., fraction of solar energy hitting the earth that is reflected), and other effects. BC is emitted with other particles (e.g. organic carbon) and criteria pollutants such as nitrogen and sulfur dioxides. Though some of these co-pollutants may exert a cooling effect on climate, the net effects of BC emissions likely contribute to global climate warming. Appendix B shows the 20 year global warming potential and black carbon equivalent values used in the results calculation. Results are presented here based on BC equivalents. The highest BC impacts are seen for charcoal briquettes, which tend to have high particulate matter emissions when processed in a kiln and also when combusted. Similarly, high emissions of particulate matter are seen for use of firewood in traditional stoves. Utilization of the liquid and gas fuels result in the lowest overall BC impacts. Some life cycle stages have negative BC equivalent impacts, which is the case when emissions of SO_x and organic carbon, pollutants with net cooling effects on the climate, are greater than the emissions of BC and other co-emitted pollutants that lead to short term warming impacts.

Table A-97. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (Uganda)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	3.80	3.80
Processed Solid Biomass	Charcoal Briquettes from Wood	0	8.41	0.0037	1.59	10.0
	Charcoal Briquettes from Bamboo	0	8.20	0.0037	1.59	9.79
	Non-Carbonized Briquettes from Sawdust	0	0.019	0.0037	2.82	2.84
	Non-Carbonized Briquettes from Crop Residues	0	-1.1E-04	2.4E-06	5.00	5.00
	Wood Pellets	0	-0.0055	0.0021	0.12	0.12
	Wood Chips	0	0.0015	9.8E-05	0.65	0.65
Liquid/Gas	Ethanol from Sugarcane	-0.010	-0.043	-0.0033	0.017	-0.040
	Ethanol from Wood	0	0.0098	5.9E-04	0.017	0.027
	Biogas from Dung	0	0	0	0.061	0.061
	LPG	0.016	-0.033	0.0012	0.057	0.042

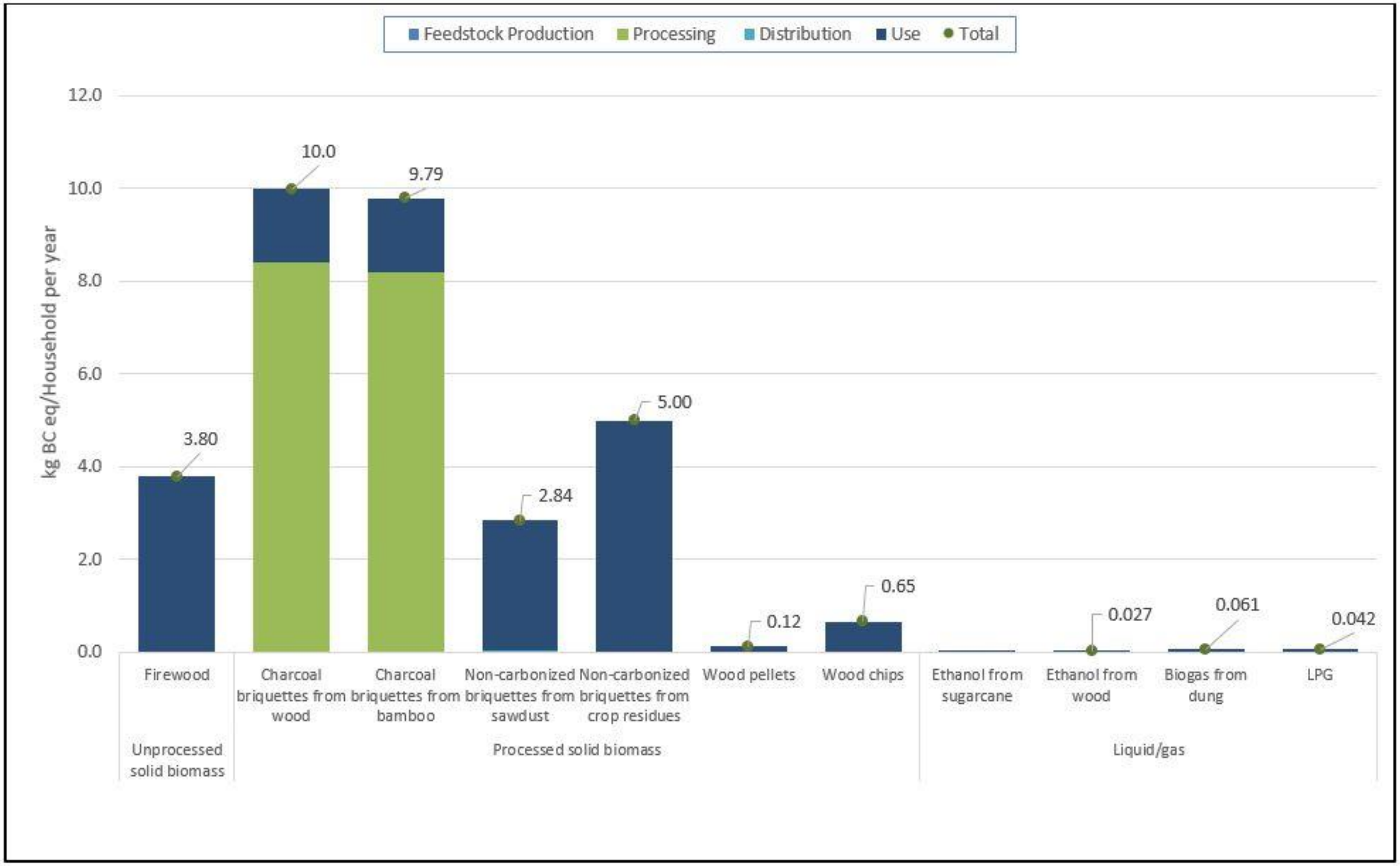


Figure A-89. Black Carbon and Short-Lived Climate Pollutant Impacts (kg BC eq) for Cooking Fuel Types (Uganda)
To produce, distribute and use cooking fuels by a single household per year

A.9.2.5 Particulate Matter Formation Potential

Table A-98 and Figure A-90 show the particulate matter formation impact results for fuels in Uganda by life cycle stage. Particulate matter can contribute to many negative health impacts such as effects on breathing and respiratory systems, damage to lung tissue, cancer, and premature death. Primary and secondary pollutants leading to particulate matter formation as well as PM2.5 are characterized here to kg PM10 eq. Charcoal briquettes lead to the greatest particulate matter formation impacts, followed by briquettes from crop residues/sawdust and firewood. For charcoal, the carbonization of the wood in the kiln dominates the overall life cycle impacts. Charcoal briquettes from bamboo have slightly lower particulate matter impacts than wood charcoal. This is because a larger portion of bamboo charcoal briquettes are estimated to be produced in hot-tail kilns; whereas, all wood charcoal briquettes in Uganda are assumed to be produced in traditional earth mound kilns. Advanced liquid fuels as well as biogas and wood pellets have comparably small particulate matter impacts.

Table A-98. Particulate Matter Formation Potential Impacts (kg PM 10 eq) for Cooking Fuel Types (Uganda)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	**Processing**	**Distribution**	**Use**	**Total**
Unprocessed Solid Biomass	Firewood	0	0	0	12.9	12.9
Processed Solid Biomass	Charcoal Briquettes from Wood	0	33.4	0.095	4.14	37.6
	Charcoal Briquettes from Bamboo	0	32.8	0.095	4.14	37.0
	Non-Carbonized Briquettes from Sawdust	0	1.00	0.095	9.61	10.7
	Non-Carbonized Briquettes from Crop Residues	0	0.0011	6.3E-05	23.3	23.3
	Wood Pellets	0	0.066	0.053	0.61	0.73
	Wood Chips	0	0.019	0.0018	6.27	6.29
Liquid/Gas	Ethanol from Sugarcane	0.68	0.21	0.092	0.0026	0.98
	Ethanol from Wood	0	0.36	0.015	0.0026	0.38
	Biogas from Dung	0	0	0	0.31	0.31
	LPG	0.40	0.45	0.039	0.29	1.18

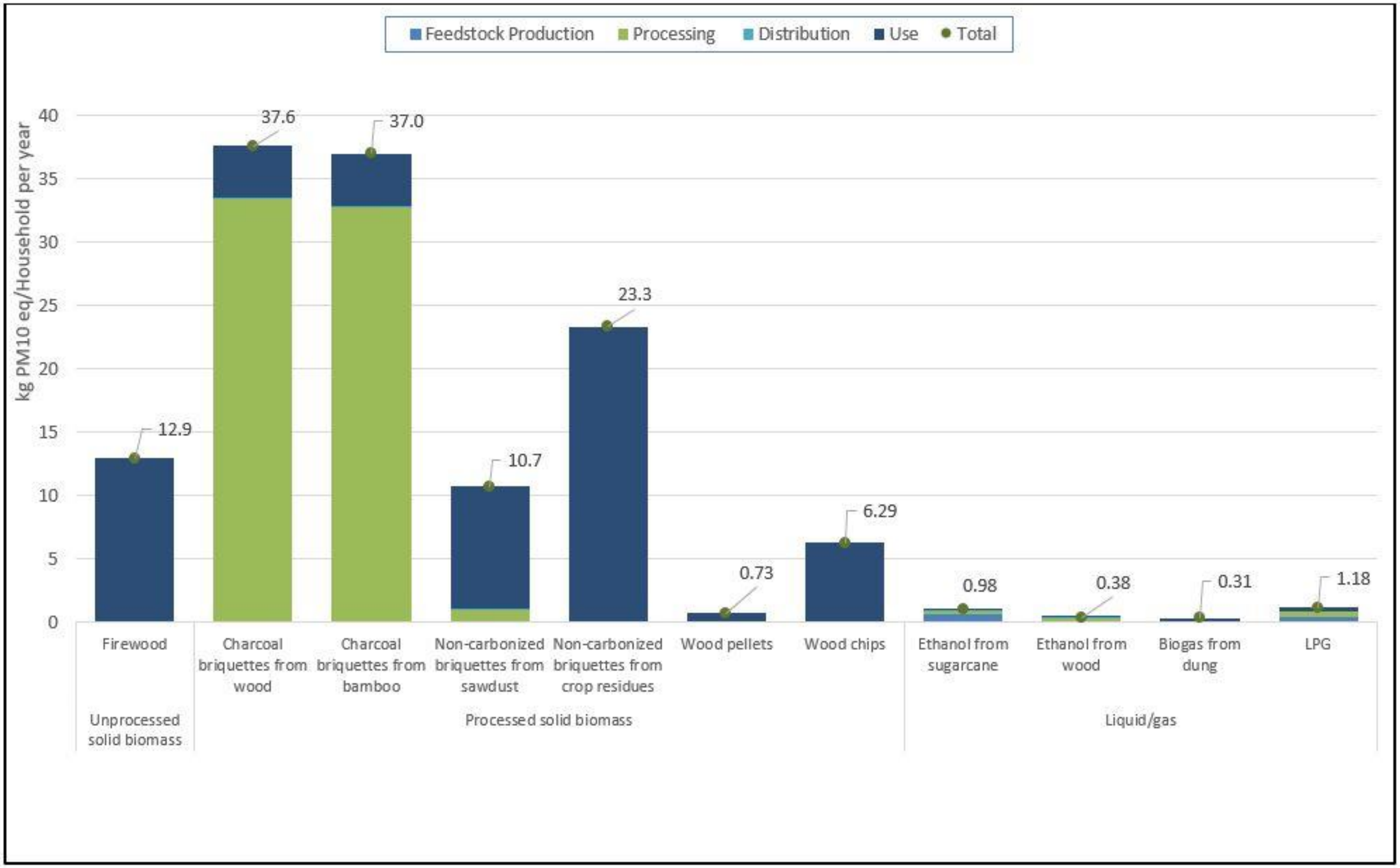


Figure A-90. Particulate Matter Formation Potential Impacts (kg PM10 eq) for Cooking Fuel Types (Uganda)
To produce, distribute and use cooking fuels by a single household per year

A.9.2.6 Fossil Fuel Depletion

Table A-99 and Figure A-91 provide the fossil fuel depletion impact results for fuels in Uganda by life cycle stage. Fossil depletion captures the consumption of fossil fuels, primarily coal, natural gas, and crude oil. All fuels are normalized to kg oil eq based on the heating value of the fossil fuel relative to the heating value of a kg of oil. The fossil depletion associated with firewood as well as biogas and ethanol from wood is negligible, as these fuels are not derived from fossil fuel, and collection of these fuels is done manually. While biomass fuels are not derived from fossil fuels, some fossil fuels may be consumed across the life cycle of these fuels for energy inputs to fuel production and processing, distribution, and disposal. Fossil depletion for wood pellets is associated with electricity usage for pelletization and some transport, while sugarcane ethanol fossil depletion is primarily from fertilizers during cane production, as well as diesel for farm operation and distribution of the feedstock and fuel. Some fossil depletion impacts are also seen for processing the wood chips and non-carbonized briquettes for the portions of these fuels that are not processed manually (as discussed in detail in Appendix B, 3% of non-carbonized and carbonized wood/bamboo briquetting is modeled as mechanized in Uganda, and 28% of wood chipping is modeled as mechanized in Uganda). Fossil depletion impacts are highest for LPG as this source of energy relies on fossil fuels.

Table A-99. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (Uganda)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed solid biomass	Firewood	0	0	0	0.033	0.033
Processed solid biomass	Charcoal briquettes from wood	0	0.027	0.018	0.0024	0.047
	Charcoal briquettes from bamboo	0	0.094	0.018	0.0024	0.11
	Non-carbonized briquettes from sawdust	0	0.15	0.018	0.019	0.18
	Non-carbonized briquettes from crop residues	0	0.22	1.2E-05	0.016	0.24
	Wood pellets	0	12.8	0.010	0.0011	12.8
	Wood chips	0	1.48	3.4E-04	0.016	1.50
Liquid/gas	Ethanol from sugarcane	72.5	16.6	2.77	0	91.9
	Ethanol from wood	0	6.36	0.0028	0	6.36
	Biogas from dung	0	0	0	0	0
	LPG	74.8	601	0.99	246	923

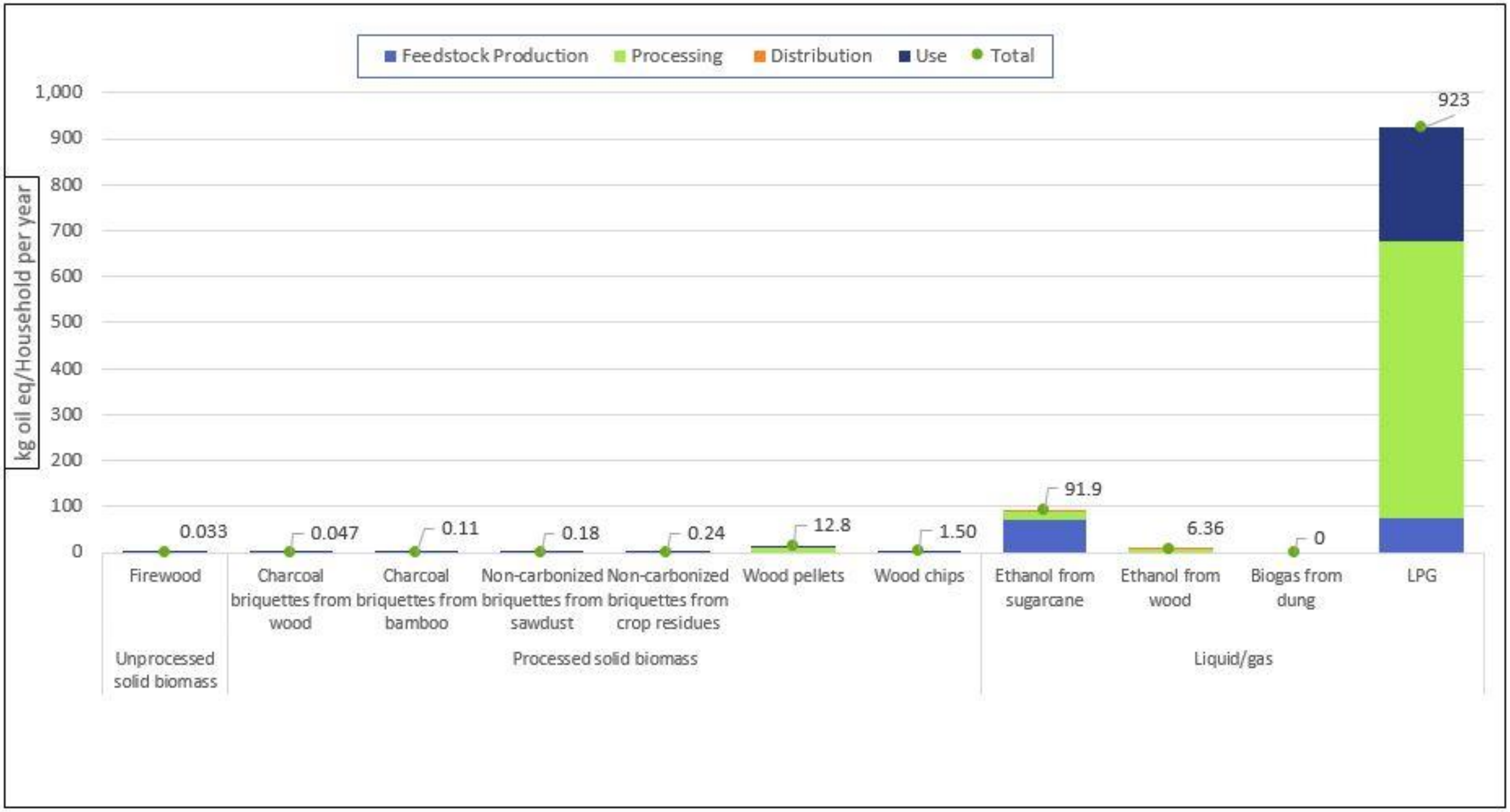


Figure A-91. Fossil Fuel Depletion Impacts (kg oil eq) for Cooking Fuel Types (Uganda)
To produce, distribute and use cooking fuels by a single household per year

A.9.2.7 Water Depletion

Table A-100 and Figure A-92 illustrate the water depletion impact results for fuels in Uganda by life cycle stage. Water depletion results are based on the volume of fresh water inputs over the life cycle of the assessed fuels. Water may be incorporated in the fuel product, evaporated, or returned to the same or different water body or to land. If the water is returned to the same water body, it is assumed the water is returned at a degraded quality, and therefore is considered consumptive use. Water consumption includes evaporative losses from establishment of hydroelectric dams but does not include the water passing through the turbine, since that water is not removed from its source. The hydropower in the electricity mix drives the overall water depletion impacts. Water depletion associated with wood pellets, the fuel with the highest water consumption impacts, is due to electricity usage during palletization (with 84% of the electricity grid mix in Uganda from hydropower).[597] Electricity also drives the minimal water depletion impacts for the 3% of briquettes pressed with motorized machines in Uganda. Water depletion impacts are also notable for sugarcane ethanol, as some irrigation is required for the cane production. Some water depletion impacts are also seen for the biogas to maintain the digester, but these are negligible when compared to the evaporative losses from hydropower in the electricity grid. Some water inputs are required for the production of LPG during crude oil extraction and petroleum refining. Water depletion impacts are negligible for the traditional biomass fuels (i.e. firewood), which are not irrigated. Because the water content of these fuels comes from the atmosphere as rainfall, the water released back to the atmosphere when the biomass is dried or combusted is not considered consumptive use.

Table A-100. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (Uganda)
To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	**Processing**	**Distribution**	**Use**	**Total**
Unprocessed Solid Biomass	Firewood	0	0	0	0.25	0.25
Processed Solid Biomass	Charcoal Briquettes from Wood	0	1.50	1.7E-04	0.018	1.52
	Charcoal Briquettes from Bamboo	0	1.35	1.7E-04	0.018	1.37
	Non-Carbonized Briquettes from Sawdust	0	16.3	1.7E-04	0.15	16.4
	Non-Carbonized Briquettes from Crop Residues	0	24.5	1.1E-07	0.12	24.7
	Wood Pellets	0	1,304	9.5E-05	0.0052	1,304
	Wood Chips	0	1.53	3.2E-06	0.12	1.65
Liquid/Gas	Ethanol from Sugarcane	330	79.6	1.63	0	411
	Ethanol from Wood	0	1.66	2.7E-05	0	1.66
	Biogas from Dung	0	19.0	0	0	19.0
	LPG	306	23.9	49.6	0	379

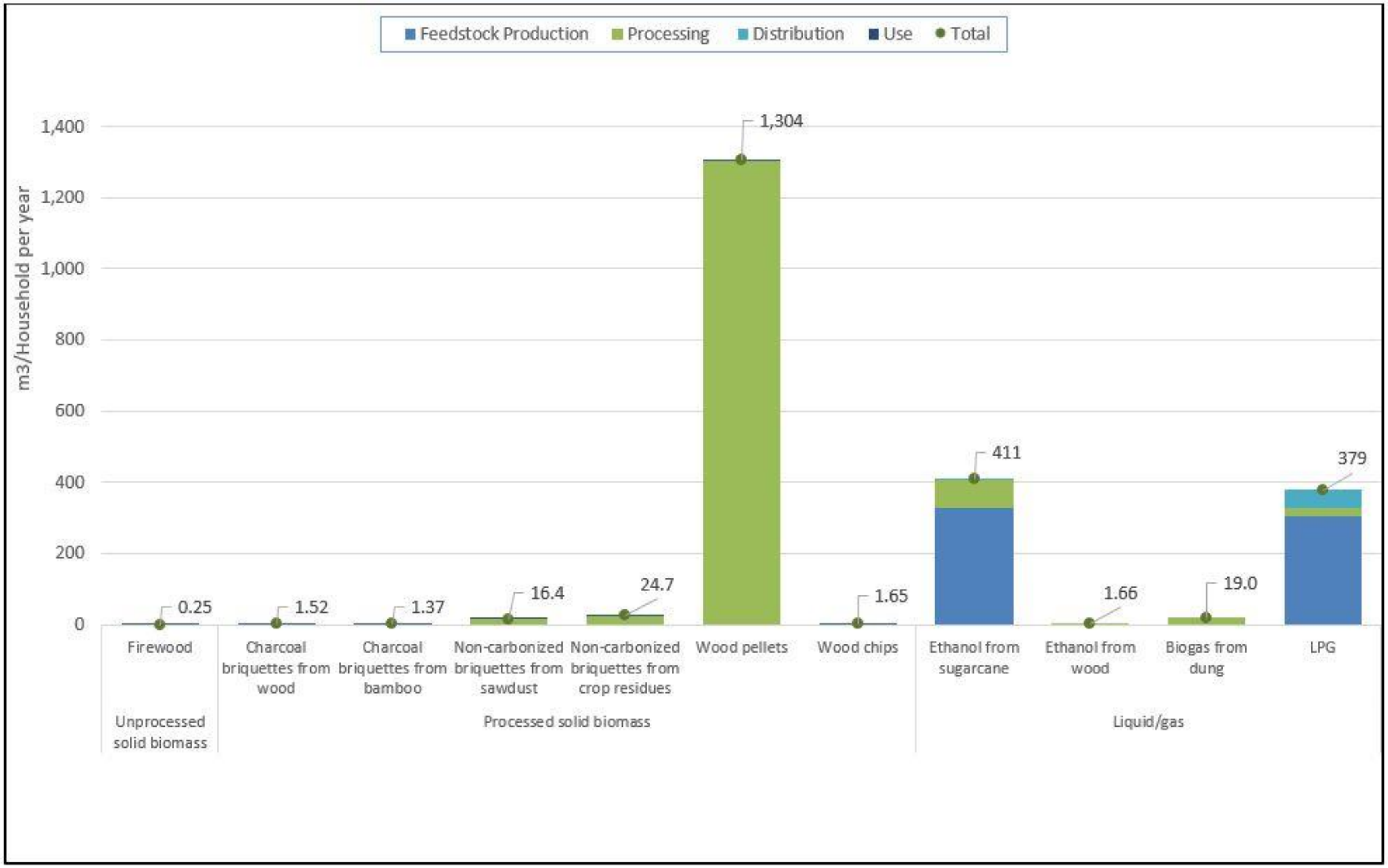


Figure A-92. Water Depletion Impacts (m^3 H_2O) for Cooking Fuel Types (Uganda)

To produce, distribute and use cooking fuels by a single household per year

A.9.2.8 Terrestrial Acidification Potential

Table A-101 and Figure A-93 show the terrestrial acidification potential impact results for fuels in Uganda by life cycle stage. Terrestrial acidification quantifies the acidifying effect of substances on their environment. Important contributing emissions include SO_2, NO_x, and NH_3. Firewood, non-carbonized briquettes from sawdust, LPG, and ethanol from sugarcane have the highest overall acidification impacts. The main contributing emissions leading to acidification potential for these fuels are SO_x and NO_x. Ethanol contains no sulfur, so there are no sulfur dioxide emissions, a main cause of acidification, for the ethanol cookstove use stage. However, there are notable emissions leading to acidification during cultivation and processing of the cane to molasses and then to ethanol. A similar magnitude of acidification impacts are seen for LPG as for ethanol. Distribution acidification impacts in Uganda are highest for transportation of the carbonized and non-carbonized briquettes since a greater mass of input fuel for the solid biomass is required to be transported a longer distance given the proximity of end users to forests in Uganda (Appendix B provides detailed discussions of the model's transportation parameters). Distribution impacts are also high for ethanol from sugarcane, which is traded as a global commodity. The lowest overall acidification impacts are seen for biogas. Because land applied digested sludge from biogas production is used by another product system, it is considered to be outside the system boundaries for this analysis; however, it is possible that this land applied digested sludge could lead to emissions of ammonia, an acidifying substance.

Table A-101. Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (Uganda)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total
		Feedstock Production	Processing	Distribution	Use	
Unprocessed Solid Biomass	Firewood	0	0	0	3.07	3.07
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.025	0.23	0.61	0.87
	Charcoal Briquettes from Bamboo	0	0.92	0.23	0.61	1.76
	Non-Carbonized Briquettes from Sawdust	0	0.018	0.23	2.27	2.51
	Non-Carbonized Briquettes from Crop Residues	0	0.0038	1.5E-04	1.27	1.28
	Wood Pellets	0	0.22	0.13	0.20	0.54
	Wood Chips	0	0.038	0.0043	1.47	1.51
Liquid/Gas	Ethanol from Sugarcane	1.82	0.90	0.27	0	3.00
	Ethanol from Wood	0	0.43	0.037	0	0.47
	Biogas from Dung	0	0	0	0.091	0.091
	LPG	0.93	1.44	0.097	0.52	2.99

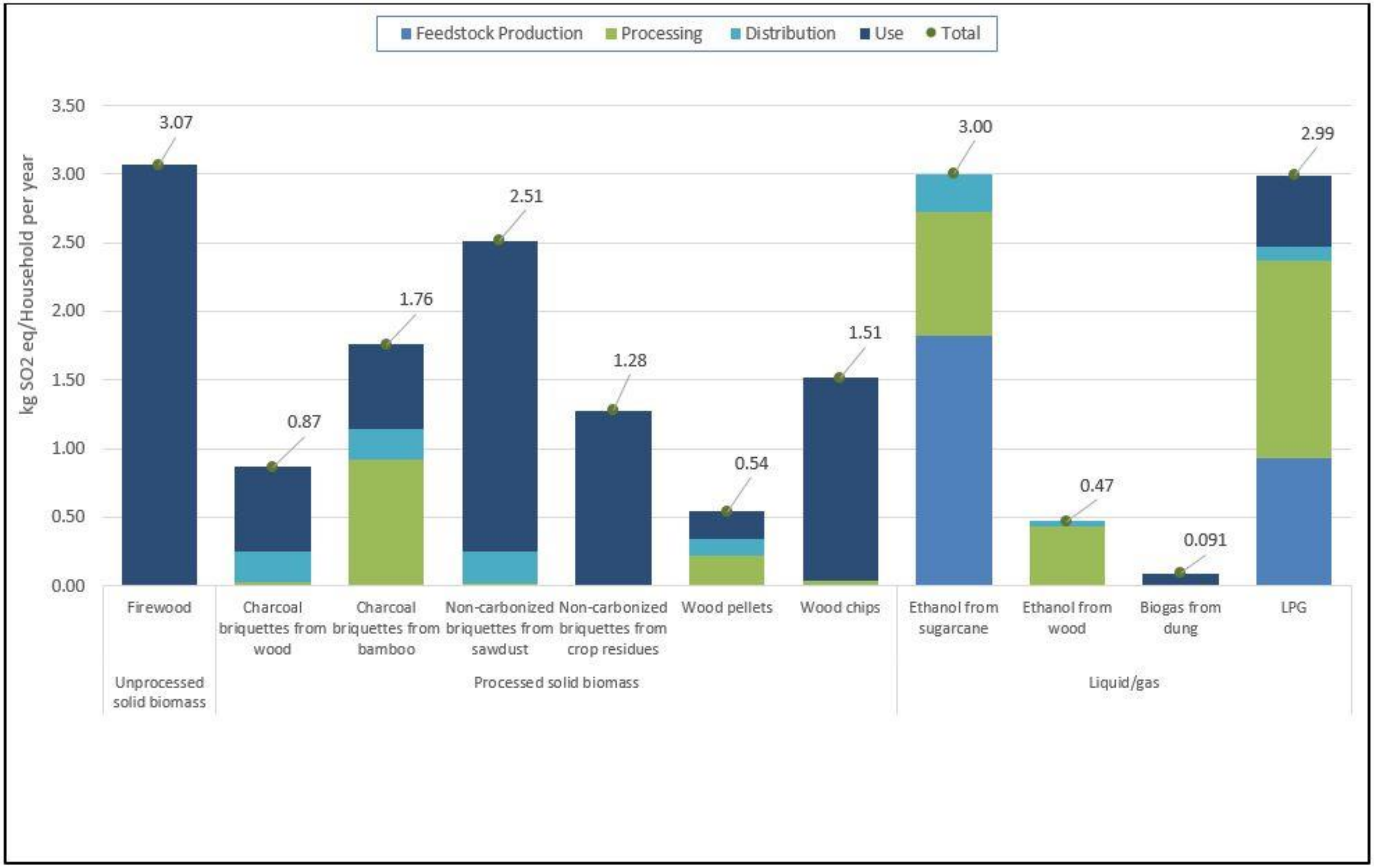


Figure A-93. Terrestrial Acidification Potential Impacts (kg SO_2 eq) for Cooking Fuel Types (Uganda)
To produce, distribute and use cooking fuels by a single household per year

A.9.2.9 Freshwater Eutrophication Potential

Table A-102 and Figure A-94 provide the freshwater eutrophication potential impact results for fuels in Uganda by life cycle stage. Eutrophication assesses the impacts from excessive load of macro-nutrients to the environment and eventual deposition in freshwater, which can result in algal blooms, oxygen depletion, and fish kills. Pollutants contributing to this category are all P based (e.g. phosphate, phosphoric acid, phosphorus). Firewood results in the highest eutrophication potential impacts. This is due to the larger ash quantity produced from Firewood compared to all other fuels. The ash from the firewood, which contains phosphorus is assumed to be land applied, which leads to soil emissions and eventual runoff into freshwater. Ash production is also the reason other processed biomass fuels have a relatively high eutrophication impact, with wood combustion at the charcoal kiln leading to the relatively high eutrophication of charcoal briquettes. The non-carbonized processed biomass fuels have slightly lower eutrophication potential impacts than traditional unprocessed biomass fuels. Because processed biomass burns more efficiently than unprocessed biomass, less fuel must be burned, leading to an overall lower quantity of ash produced. While impacts are comparably smaller for ethanol, there are some eutrophication impacts occurring from use of phosphorus based fertilizer in sugarcane production. There are no eutrophication impacts associated with biogas. Application of the digested sludge from the biogas system would likely lead to some eutrophication impacts, but utilization of this useful co-product is outside the system boundaries of this study. The digested sludge impacts are allocated to the product system it serves (i.e. nutrients for crop production). Impacts from fossil based fuels and biomass pellets are minimal compared to the traditional fuels.

Table A-102. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (Uganda)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				Total
		Feedstock Production	Processing	Distribution	Use	
Unprocessed Solid Biomass	Firewood	0	0	0	0.81	0.81
Processed Solid Biomass	Charcoal Briquettes from Wood	0	0.35	1.9E-07	0.058	0.41
	Charcoal Briquettes from Bamboo	0	0.34	1.9E-07	0.058	0.40
	Non-Carbonized Briquettes from Sawdust	0	0.0032	2.0E-07	0.47	0.48
	Non-Carbonized Briquettes from Crop Residues	0	2.3E-05	1.3E-10	0.39	0.39
	Wood Pellets	0	0.0015	1.1E-07	0.017	0.018
	Wood Chips	0	2.2E-04	3.7E-09	0.39	0.39
Liquid/Gas	Ethanol from Sugarcane	0.20	0.013	2.3E-04	6.3E-06	0.21
	Ethanol from Wood	0	1.3E-05	3.1E-08	6.3E-06	1.9E-05
	Biogas from Dung	0	0	0	0	0
	LPG	0.043	0.0033	6.0E-05	0	0.047

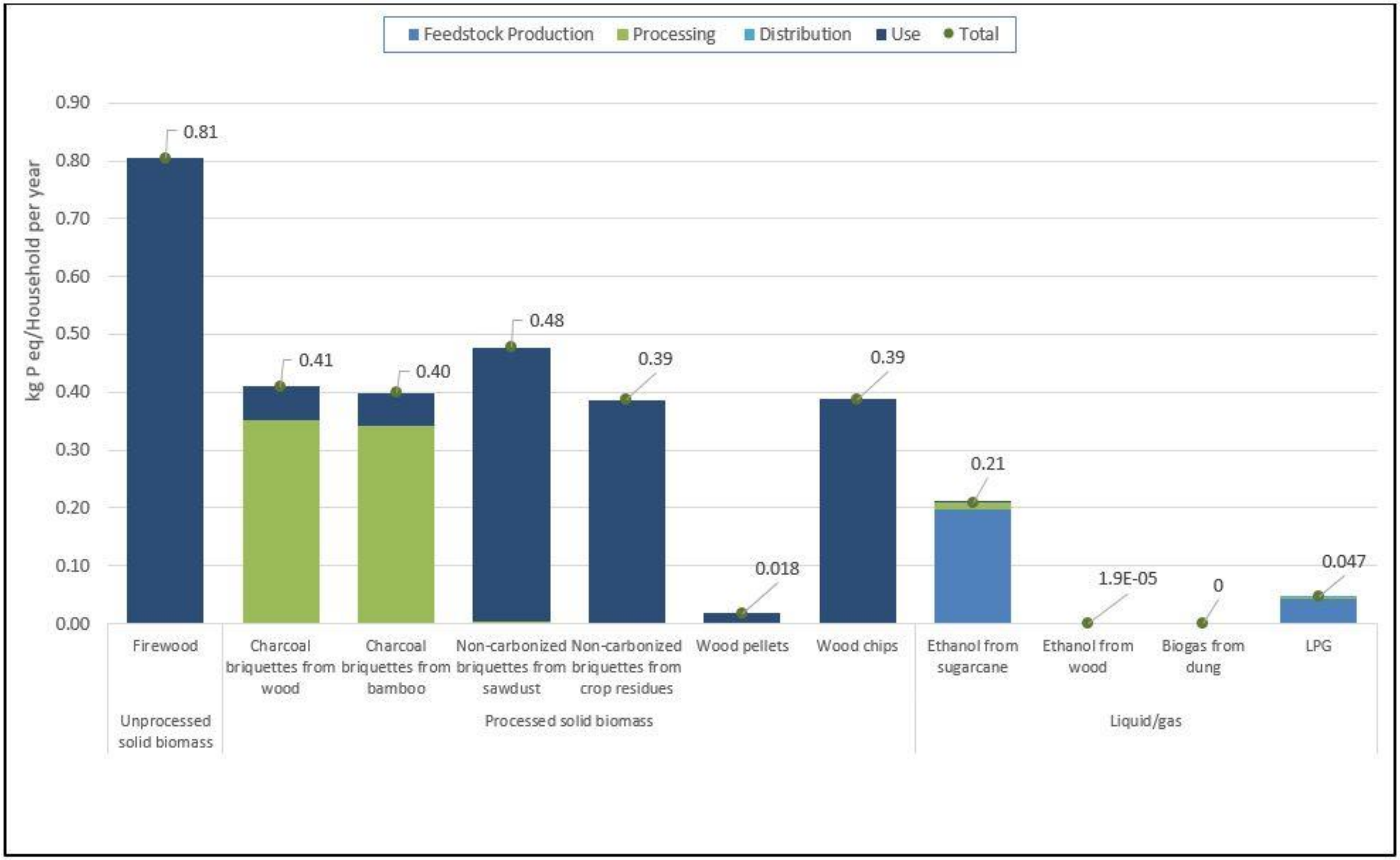


Figure A-94. Freshwater Eutrophication Potential Impacts (kg P eq) for Cooking Fuel Types (Uganda)
To produce, distribute and use cooking fuels by a single household per year

A.9.2.10 Photochemical Oxidant Formation Potential

Table A-103 and Figure A-95 present the photochemical oxidant formation potential impact results for fuels in Uganda by life cycle stage. The photochemical oxidant formation (i.e. smog formation) results are an indicator of the potential for formation of reactive substances that cause harm to human health and vegetation. Results are characterized here to kg of non-methane volatile organic compounds (NMVOC) eq. Some key emissions for cookstove fuel systems that contribute to photochemical oxidant formation include carbon monoxide, methane, nitrogen oxides, NMVOCs, and sulfur dioxide. Firewood and charcoal briquettes lead to the greatest photochemical formation impacts, followed by processed biomass fuels. For charcoal briquettes, impacts are dominated by the fuel processing stage (carbonization in a kiln). Photochemical oxidant formation impacts are relatively small for the liquid fuels, processed non-carbonized biomass and biogas.

Table A-103. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (Uganda)

To produce, distribute and use cooking fuels by a single household per year

		Life Cycle Stage				
		Feedstock Production	Processing	Distribution	Use	Total
Unprocessed Solid Biomass	Firewood	0	0	0	138	138
Processed Solid Biomass	Charcoal Briquettes from Wood	0	139	0.39	28.7	168
	Charcoal Briquettes from Bamboo	0	140	0.39	28.7	169
	Non-Carbonized Briquettes from Sawdust	0	0.69	0.39	102	103
	Non-Carbonized Briquettes from Crop Residues	0	0.0025	2.6E-04	18.1	18.1
	Wood Pellets	0	0.38	5.9E-06	0.61	0.98
	Wood Chips	0	0.065	0.0074	66.7	66.7
Liquid/Gas	Ethanol from Sugarcane	1.01	0.28	0.28	0.37	1.94
	Ethanol from Wood	0	0.75	0.063	0.37	1.18
	Biogas from Dung	0	0	0	0.48	0.48
	LPG	2.14	1.17	0.17	6.30	9.77

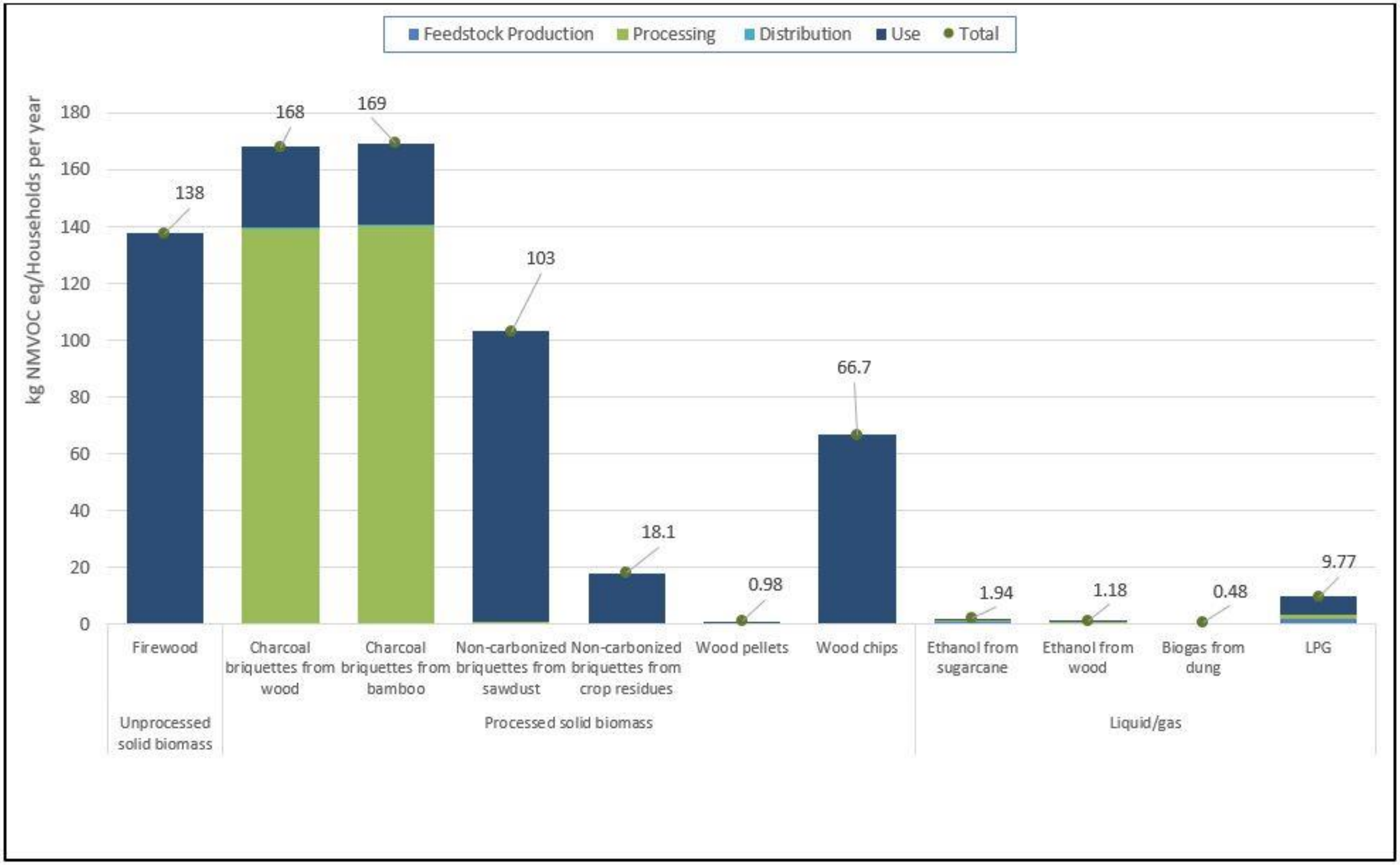


Figure A-95. Photochemical Oxidant Formation Potential Impacts (kg NMVOC eq) for Cooking Fuel Types (Uganda)
To produce, distribute and use cooking fuels by a single household per year

A.9.3 Economic Indicators for Uganda

A.9.3.1 Fuel Use

Figure A-96 shows the percentages of the population in Uganda that utilize various types of fuel as their primary cooking fuel. Almost 86 percent of the population use biomass (primarily firewood) as their primary cooking fuel. This is the highest percentage of biomass use by the countries included in this analysis.[598,599,600,601] Firewood is most commonly used by low-income consumers in rural and peri-urban areas.[602] About 13 percent of the population relies on charcoal, which is most commonly used by middle-income peri-urban consumers and those living in urban areas.[603]

Other fuels are currently being used on a limited basis. Very small percentages of the population use LPG, kerosene, or other fuels.[604] LPG use is limited because low-income consumers often cannot afford to purchase large cylinders, and because it is logistically difficult to distribute LPG to remote rural areas.[605] Smaller cylinders that are less expensive and more easily transported could help with both of these consumer-driven issues; however, since smaller cylinders will be used up more quickly than large cylinders, distributors would likely need to make more frequent deliveries, or consumers would need to keep backup cylinders on hand to ensure an uninterrupted supply of fuel. Non-carbonized and carbonized briquettes are being sold by small enterprises, but awareness and uptake are generally low.[606,607] There are some small enterprises producing crop residue briquettes and wood pellets, but these are in the early stages of development.[608] Biogas is used on a very limited basis, as the capital equipment costs are often out of reach for most consumers.[609] Wood chips are not used at all.[610]

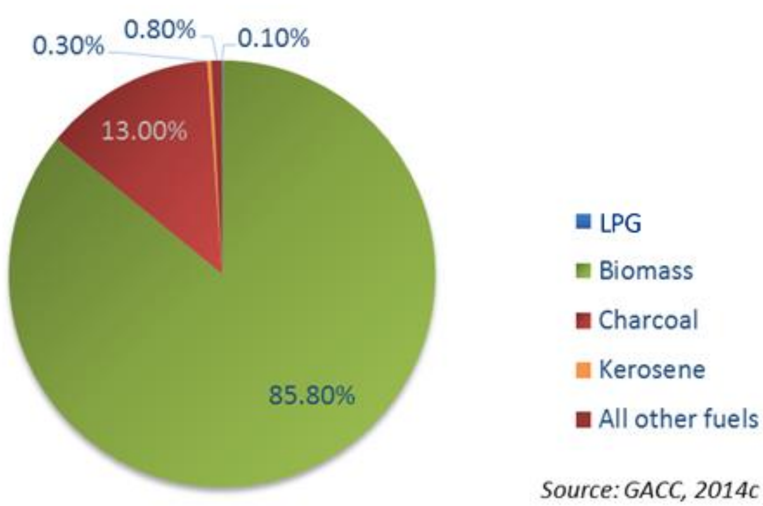


Figure A-96. Current Cooking Fuel Mix in Uganda.

A.9.3.2 Fuel Imports, Exports, Production, and Demand in Uganda

Table A-103 shows the levels of imports, exports, production, and demand (assumed to be equal to current consumption) of several fuels in Uganda. The data on total and household demand do not differentiate between fuel use for cooking and fuel use for other purposes such as heating. Firewood is the dominant cooking fuel used in Uganda,[611,612] and overall about 41.3 million tonnes of firewood are produced each year.[613,614] Forest land in Uganda decreased by over three percent per year from 2005 to 2010[615], so some of the current use of wood as cooking fuel will likely need to be shifted to alternative fuels. The next most commonly used cooking fuel is charcoal, and the 956,812 tonnes of demand can be provided almost entirely by domestic production. The charcoal produced is reported to be wholly consumed by households.[616] Uganda trades some ethanol,[617] but data on production and demand of ethanol overall are not available. Other fuels, such as LPG and wood chips, are reported as being traded or consumed in small amounts compared to the other fuels.[618,619]

Table A-104. Fuel Imports, Exports, Production, and Demand in Uganda (Tonnes per Year)

Fuel	Imports	Exports	Production	Demand		Sources
				Total	Household	
LPG	5,670	No data	No data	5,400	4,320	UNSD, 2011
Ethanol	9	316	No data	No data	No data	UNSD, 2013
Firewood	No data	42	41,285,000	No data	No data	UNSD, 2013 FAO, 2014
Charcoal Briquettes	40	120	956,892	956,812	956,812	UNSD, 2011
Wood Chips	No data	2	No data	No data	No data	UNSD, 2013

A.9.3.3 Fuel Cost in Uganda

Figure A-97 shows the price per household per year for the cooking fuels in Uganda for which cost data are available. Charcoal is the most expensive fuel, at $475 per household per year, while LPG is the second most expensive fuel, with annual costs of $338 per household.[620] Purchased firewood[621] and non-carbonized crop residue briquettes are similar in price, between $260 and $290 per household per year.[622,623] As in other countries, ongoing deforestation is reducing the supply of wood, which will likely put upward pressure on firewood prices, and rural consumers who currently collect firewood for free may have to begin purchasing it.[624]

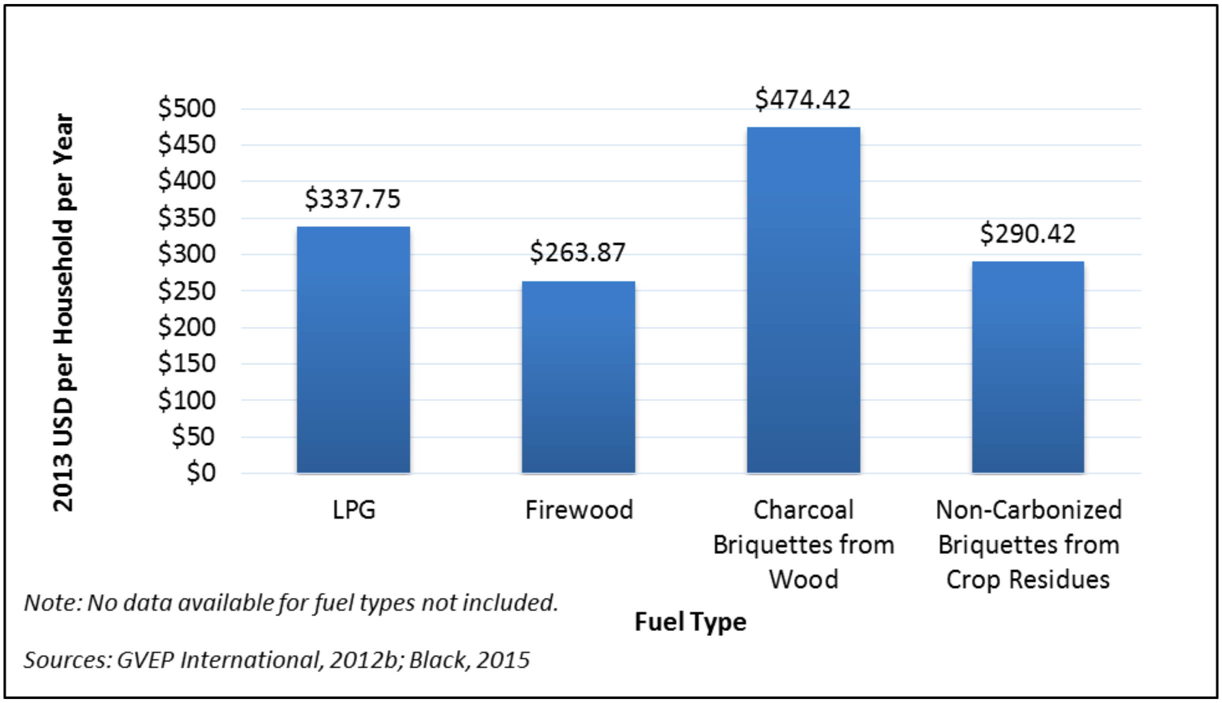


Figure A-97. Fuel Cost Indicator for Cooking Fuels in Uganda.

A.9.4 Social Indicators for Uganda

A.9.4.1 Government Policies/Programs

Given the relative innovation of the feedstock-fuel combinations in the present study, limited information is available from Uganda's government regarding the promotion of or resistance to specific cookfuels. Cooking with biogas is promoted under the National Biogas Program, which aims to install 12,000 biogas digesters in five years, presumably beginning in 2011 or 2012,[625] and data suggest the LPG sector is primarily driven by private industry as opposed to government policies.[626] Due in part to 75 percent deforestation in Uganda, the government has emphasized sustainable forestry in its 2011/12 - 2021/22 National Forest Plan,[627] and its Energy and Renewable Energy policies (2002 and 2007, respectively[628]) call for the sustainable and efficient use of biomass fuel supplies (as part of a larger move towards energy security).[629] Moreover, the government has begun actively supporting producers of charcoal briquettes from wood with financial incentives in order to encourage the use of more efficient types of woodfuel.[630,631] In addition to direct financial support (e.g., a $5,000 grant to an enterprise), the government has also provided symbolic support by having government officials attend promotional events.[632] Despite these forms of encouragement, a variety of taxes (value-added, employment, etc.) continue to disadvantage legitimate producers of charcoal.[633]

Although it ended recently, the Promotion of Renewable Energy and Energy Efficiency Programme (PREEP)—a public-private partnership between the Ministry of Energy and Minerals and local NGOs—promoted sustainable charcoal production, increased access to modern biomass energy technologies, and more from 2007 to 2014. Both the framework and lessons learned (the program struggled to develop markets in rural areas where households found modern cookstoves too expensive) could provide useful guidance for future initiatives.[634]

Fuel-neutral activities also play a role in shaping the clean cooking sector. For example, Uganda has used Clean Development Mechanism credits to propose or fund approximately 25 projects to expand the use of clean cookstoves. Similarly, the Improved Cookstove for East Africa program (2011-present)—a collaboration between the Uganda Carbon Bureau, Care International, and the Nordic Climate Facility—uses carbon financing to provide sustainable access to affordable and efficient cookstoves. The program, however, has experienced delays in registering products in Uganda and difficulties identifying suitable stove producers to work with.[635] Though not specific to the energy sector, but with the potential to improve women's access to the clean cookstove and cookfuel labor market, Uganda's 2007 National Gender Policy seeks to combat issues such as discrimination against women in the formal economy and the traditional cultural acceptance of domestic violence.[636]

A.9.4.2 Supply & Access Challenges

The most commonly used cooking fuel in Uganda is firewood, which is gathered freely by 64 percent and 41 percent of rural and periurban consumers, respectively.[637] Given the informal, fragmented nature of the firewood sector, however, data on reliability of firewood acquisition are not currently available. Insights into the reliability of acquiring LPG and charcoal briquettes from wood, however, are available. LPG infrastructure in Uganda is not well developed and all LPG is processed at Mombasa, Kenya.[638] Having all processing done in a single location introduces vulnerabilities and uncertainties into the supply chain as well as increases the price to end-users.

Although the wood-based charcoal supply chain has traditionally been seen as reliable in Uganda,[639] insights from industry suggest there is more variability than conventional wisdom accounted for. For example, fluctuations in feedstocks, unpredictable weather patterns, variability in labor productivity, and an inconsistent ability to maintain machinery all have a material impact on the ability of wood-based charcoal producers to maintain consistent supplies.[640]

A.9.4.3 Distribution & Adoption Challenges

Despite the presence of private and public initiatives working to raise awareness,[641] a key barrier to the adoption of the target fuels in Uganda is a lack of knowledge regarding the social and environmental benefits of using nontraditional fuels.[642,643] On the other hand, one charcoal enterprise states they see households from a range of socioeconomic classes using charcoal for cooking, with some adding in gas and solar energy.[644] This suggests that limited awareness is an issue in some (most likely rural) communities, whereas the perceived energy ladder, [645] which associates increases in wealth and education with the adoption of improved fuels, may be less applicable in urban settings.

Ugandan households using biogas from animal dung face a unique set of issues. In addition to the high upfront costs associated with biogas systems and the lack of available capital in rural markets,[646] a study found that 34 percent of surveyed households were inconvenienced due to challenges with mixing dung, an increased need for water, and performance issues with the biogas systems themselves.[647] Other issues relate to the foods cooked over biogas: some users find that biogas systems produce a negative aroma in their dishes[648] and other users report that traditional foods such as matooke (cooked starchy banana), which is mashed and left on the fire for hours, are impossible to cook over biogas.[649] Alternatively, in parts of the country where lighter foods such as rice and potatoes are consumed, households find they can use biogas most of the time without needing to use supplementary energy sources.[650]

A study on the wood-based charcoal sector offers insights into challenges producers face when trying to scale up their operations. Primary barriers include:

- Technological Challenges – limited technical capacity, limited access to spare parts, lack of localized technologies due to poor investment in research and development,
- Financial Challenges – high upfront costs of briquetting infrastructure, lack of experience with the briquette sector among commercial lenders, perceived credit risks among entrepreneurs, limited number of briquette developers (lack of economies of scale),
- Regulatory Challenges – uncertainty in scope of regulations, regulatory gaps, low enforcement capacities,
- Knowledge Challenges – limited entrepreneurial skills, lack of scalable business models, and
- Operational Challenges – competition from alternative sources (i.e., limited promotional/marketing work has been done to differentiate briquettes from alternative fuels), inconsistent feedstock supplies, competing feedstock and labor uses, and low quality of final product.[651]

A.9.4.4 Protection & Safety

The only fuel-specific safety concerns for which data are available in Uganda relate to the manual gathering of firewood from remote locations. In such situations, the primary risk for women and young girls is physical and sexual violence.[652] For example, in 2014 in the Nakivale refugee camp, 41 percent of households reported incidences of violence during firewood collection. Of those reporting incidences of violence, specific outcomes include confiscation of firewood (23 percent), beating (20 percent), bodily injury (12 percent), assault (10 percent), attempted rape (5 percent), and rape (4 percent), with the remaining 26 percent presumably representing incidents comprising multiple forms of assault.[653] Men and women alike are at risk for encounters with animals, such as venomous snakes.[654]

For purchased fuels considered in this analysis (e.g., LPG or ethanol), no safety issues during the purchase of the fuels were found within the literature. Collection of crop residues usually occurs somewhat close to the household, and no safety issues were found in the literature.

A.9.4.5 Time & Drudgery

Due to land degradation and poor watershed management, time spent collecting firewood in Uganda takes an average of 3 hours per day for those living in urban areas and 6 hours per day for those living in rural areas.[655] On average, women refugees collect firewood 8.3 times per month and girls age 17 and under collect firewood 7.2 times per month.[656] The average distance travelled roundtrip to gather firewood is between 5.7 and 10 kilometers.[657,658] If forests continue to disappear at their current rate—around 2 percent per year over recent years[659]—fuel collection times and distances are expected to increase.[660] Corroborating this projection is a study that found women and girls would save an estimated 240 hours per year if woodlots were within 30 minutes of their communities.[661] One promising means of making the most of manually collected firewood is charcoal briquetting. Household briquetting systems still require whole wood as a feedstock, but fuel collection trips are more cost-effective because using the end briquette product is more efficient than burning firewood. Moreover, during the two to three hours per day that wood is carbonizing in a kiln, women's time can be spent attending to other household obligations such as cooking or washing clothes.[662]

In addition to the time it takes to manually gather firewood, it is also time-consuming to cook using firewood. On average, women and men spend 98 minutes and 86 minutes per day cooking over firewood, respectively, on days that they cook. The difference in cooking times is attributable to the inclusion of refueling time in the study.[663] To put this in perspective, cooking over nontraditional fuels such as charcoal briquettes from wood and biogas from animal dung takes around 30 minutes per day.[664] Another alternative to firewood is briquettes from non-carbonized crop residues. Although cook-time data are not available, anecdotal evidence suggests non-carbonized crop residue briquettes do not burn as hot as charcoal briquettes from wood and are better used for keeping cooked foods warm than for cooking them initially.[665] To a lesser extent, the same holds for biogas from animal dung, which is best suited for light cooking rather than the preparation of traditional foods such as sweet potatoes or cassava that require long cooking times.[666]

A.9.4.6 Income Earning Opportunities

Given the newness of the feedstock-fuel combinations in the present study, limited information regarding the income earning opportunities associated with specific cookfuels is available. One fuel for which data are available is charcoal briquettes from wood, which represent about 13 percent of the cookfuel market[667] and are primarily consumed by urban users.[668] Income earning opportunities for charcoal briquettes from wood vary by enterprise because smaller establishments tend to use less mechanized, more labor-intensive methods. Although such establishments may only directly employ between 15-40 people, they can provide income indirectly to an additional 15-30 people who provide feedstocks. Moreover, retail and distribution networks may employ another 5-80 people per enterprise, depending on the size and scope of operations.[669] Relatively inexpensive alternatives and high capital costs, which limit both production expansion and marketing capabilities, makes short-term sustainability of these employment opportunities a challenge. On the other hand, annual charcoal demand is estimated at 956,812 tonnes,[670] and as prices of wood and charcoal increase, the charcoal industry is projected to become more and more profitable.[671]

Income earning opportunities for other fuels such as non-carbonized briquettes from crop residues (annual production of 5,000-7,000 tonnes, representing less than one percent of the cookfuel market[672]) and biogas from animal dung (which produces a bioslurry that can be resold,[673] presumably as fertilizer) exist, but are less well understood. As an example of the former, Margret Kisakye, after receiving training from GVEP International's Developing Energy Enterprises Programme, was able to establish a successful, 1,000 kg per month briquetting business utilizing charcoal dust, grass, and cassava as feedstocks. As Kisakye's business grew, she transitioned from making briquettes by hand to using a pressing machine and carbonization kiln.[674]

Although not operating at the household- or community-level, another example of an enterprise producing non-carbonized briquettes from agricultural residues is Kampala Jellitone Suppliers (KJS). KJS feedstocks include rice husks, coffee pulp, maize stalks, and sawdust. Once the feedstocks are compressed and extruded into briquettes, they are sold to 36 institutions, including schools, hospitals, and food-processing companies, where they have displaced firewood and, to a lesser extent, charcoal as the primary fuel source. KJS indicates that there is demand for their product at the domestic level and development work is underway.[675] Relatedly, recently-funded feasibility studies are underway for wood-based pellets and bamboo-based charcoal briquettes.[676] Sugarcane-based ethanol represents another opportunity market, but its use is currently negligible.[677]

A.9.4.7 Opportunities for Women Along the Value Chain

According to the Global Alliance for Clean Cookstoves 2013 Results Report, the clean cookstove industry in Uganda currently has 4,564 employees (6 percent of whom are women) and 891 microentrepreneurs (38 percent of whom are women).[678] Although there are limited data available to estimate potential increases of skills for women with respect to most fuels, some insights are available for charcoal briquettes made from wood, which offer opportunities for many people, and women in particular.[679] While larger, more mechanized producers of charcoal briquettes tend to primarily employ men (approximately 77 percent of the sector), smaller lower tech enterprises use a larger percentage of women in production (70 to 80 percent).[680] For Ecofuel Africa, an organization that has trained over 1500 women, female entrepreneurs have increased their incomes over 100 percent.[681] In order to achieve these results and sustain women's involvement in the industry, successful enterprises tend to provide training classes that improve the technical, financial, and logistical skills that are often lacking among community-level producers.[682] Even when working with organizations and initiatives providing comprehensive support, female entrepreneurs in Uganda face substantial barriers relative to their male counterparts. Women tend to have less collateral and subsequently have greater difficulty obtaining loans. Moreover, as women are responsible for most domestic obligations, their ability to travel and take part in business development opportunities are limited.[683]

Complete citations for data sources used within the study are presented in Appendix C.

[1] World Bank, 2015
[2] USDA FAS, 2014b
[3] Berrah, 2007
[4] Wu, 2015
[5] Berrah, 2007
[6] King, 2015
[7] FAO, 2010
[8] FAO, 2010
[9] Zhou et al., 2007
[10] IEA, 2011
[11] IEA, 2014
[12] GACC, 2014c
[13] GACC, 2014c
[14] NBS China, 2008
[15] Wu, 2015
[16] Wu, 2015
[17] UNSD, 2011

[18] UNSD, 2011
[19] GACC, 2014c
[20] Wu, 2015
[21] OECD/FAO, 2014
[22] USDA FAS, 2014b
[23] Wu, 2015
[24] USDA FAS, 2014b
[25] USDA FAS, 2014b
[26] FAO, 2014
[27] UNSD, 2013
[28] FAO, 2014
[29] Mainali et al., 2012
[30] Wu, 2015
[31] Mainali et al., 2012
[32] Christiaensen, 2012
[33] Mainali et al., 2012
[34] FAO, 2010
[35] Wu, 2015
[36] Dalberg, 2014
[37] USDA FAS, 2014b
[38] USDA FAS, 2014b
[39] Berrah et al., 2007
[40] Wu, 2015
[41] Berrah et al., 2007
[42] Wu, 2015
[43] Wu, 2015
[44] ASTAE, 2013
[45]ASTAE, 2013
[46] Christiansen, 2012
[47] ASTAE, 2013
[48] ASTAE, 2013
[49] ASTAE, 2013
[50] ASTAE, 2013
[51] Wu, 2015
[52] Wang, 2012
[53] Wu, 2015
[54] Wu, 2015
[55] ASTAE, 2013
[56] Wu, 2015
[57] ASTAE, 2013
[58] ASTAE, 2013
[59] Ramani & Heijndermans, 2003
[60] Wang, 2012
[61] Ramani & Heijndermans, 2003
[62] Wu, 2015
[63] ASTAE, 2013
[64] GACC, 2013
[65] Wu, 2015
[66] Dalberg, 2013
[67] Masoodi, 2016
[68] Dalberg, 2013
[69] World Bank, 2010
[70] FAO, 2010
[71] Lambe & Atteridge, 2012
[72] Habib et al., 2004
[73] SEWA, 2015

[74] Dalberg, 2013
[75] TERIIN, 2010
[76] Dalberg, 2013
[77] IEA, 2014
[78] NARI, 2004
[79] UNSD, 2013
[80] SEWA, 2015
[81] WLPGA, 2014
[82] Thurber et al., 2014
[83] Bikash et al., 2013
[84] Thurber et al., 2014
[85] Dalberg, 2013
[86] IPC, 2014
[87] Gov. of India, 2015
[88] Dalberg, 2013
[89] Jayaswal, 2013
[90] Setty, 2015
[91] Dutta, 2015
[92] Kojima et al., 2011
[93] Kojima et al., 2011
[94] Dalberg, 2013
[95] Dalberg, 2013
[96] Ministry of New and Renewable Energy, 2012
[97] Dalberg, 2013
[98] Dalberg, 2013
[99] Barnes et al., 2012
[100] Dalberg, 2013
[101] FAO, 2010
[102] Dalberg, 2013
[103] Dalberg, 2013
[104] IPC, 2014
[105] IPC, 2014
[106] IPC, 2014
[107] Barnes et al., 2012
[108] ESMAP, 2002
[109] UNDP, 2003
[110] Barnes et al., 2012
[111] WLPGA, 2014
[112] ESMAP, 2002
[113] ARTI India, 2015
[114] Bhojvaid et al., 2014
[115] Pandey & Chaubal, 2011
[116] Kojima et al., 2011
[117] Dalberg, 2013
[118] Kojima et al., 2011
[119] Dalberg, 2013
[120] Dalberg, 2013
[121] Lambe & Atteridge, 2012
[122] WLPGA, 2014
[123] Dalberg, 2013
[124] Dalberg, 2013
[125] Dalberg, 2013
[126] Dalberg, 2013
[127] ESMAP, 2002
[128] Bhojvaid et al., 2014
[129] ESMAP, 2004

[130] Singh and Gundimeda, 2014
[131] Barnes et al., 2012
[132] Parikh, 2011
[133] Dalberg, 2013
[134] Barnes et al., 2012
[135] Singh and Gundimeda, 2014
[136] ESMAP, 2004
[137] Singh & Gundimeda, 2014
[138] UNDP, 2011
[139] WLPGA, 2014
[140] ESMAP, 2004
[141] Dalberg, 2013
[142] Barnes et al., 2012
[143] ESMAP, 2004
[144] Bhojvaid et al., 2014
[145] WLPGA, 2014
[146] Dalberg, 2013
[147] GACC, 2014b
[148] Setty, 2015
[149] WLPGA, 2014
[150] Dalberg, 2013
[151] ESMAP, 2002
[152] Setty, 2015
[153] GACC, 2013
[154] Dalberg, 2013
[155] Dalberg, 2013
[156] WLPGA, 2014
[157] Dalberg, 2013
[158] Dalberg, 2013
[159] World Bank, 2014a
[160] Accenture, 2012a
[161] World Bank, 2015
[162] Asaduzzaman et al., 2010
[163] Asaduzzaman, 2010
[164] Accenture, 2012a
[165] Accenture, 2012a
[166] Accenture, 2012a
[167] Arif, et at., 2011
[168] Accenture. 2012a
[169] FAO, 2010
[170] Accenture, 2012a
[171] Accenture, 2012a
[172] ASTAE, 2013
[173] Shanavas & Kumar, 2006
[174] USAID, 2013
[175] GACC, 2014c
[176] Accenture, 2012a
[177] Shahjahan, 2015
[178] Accenture, 2012a
[179] Shahjahan, 2015
[180] REIN, 2013
[181] Shahjahan, 2015
[182] Shahjahan, 2015
[183] EMRD, 2009
[184] Accenture, 2012a
[185] UNSD, 2011

[186] OECD/FAO, 2014
[187] FAO, 2014
[188] Accenture, 2012a
[189] Shahjahan, 2015
[190] Shahjahan, 2015
[191] Accenture, 2012a
[192] GIZ, 2012
[193] GIZ, 2012
[194] Accenture, 2012a
[195] GIZ, 2012
[196] Accenture, 2012a
[197] Accenture, 2012a
[198] Shahjahan, 2015
[199] FAO, 2010
[200] Accenture, 2012a
[201] Accenture, 2012a
[202] Accenture, 2012a
[203] Shahjahan, 2015
[204] OECD/FAO, 2014
[205] GACC, 2014c
[206] Shahjahan, 2015
[207] GACC, 2014c
[208] GACC, 2014c
[209] Shahjahan, 2015
[210] Ahiduzzaman, 2007
[211] Accenture, 2012a
[212] Fatema, 2005
[213] Fatema, 2005
[214] Fatema, 2005
[215] Shahjahan, 2015
[216] Fatema, 2005
[217] Accenture, 2012a
[218] Accenture, 2012a
[219] Barnes et al., 2012
[220] Ahiduzzaman, 2007
[221] Accenture, 2012a
[222] WLPGA, 2014
[223] Shahjahan, 2015
[224] Ashden, 2012
[225] Grameen, 2015a
[226] Grameen, 2015b
[227] Grameen, 2015a
[228] Grameen, 2015d
[229] GACC, 2013
[230] Berthaud et al., 2004
[231] Fatema, 2005
[232] Asaduzzaman et al., 2010
[233] Fatema, 2005
[234] Shahjahan, 2015
[235] PRB, 2015
[236] ESF, 2013
[237] FAO, 2010
[238] ESF, 2013
[239] ESF, 2013
[240] World Bank, 2015
[241] Grinnell, 2015

[242] Pennise et al., 2001
[243] ESF. 2013
[244] IEA. 2012
[245] ESF, 2013
[246] GACC, 2014c
[247] Wang, et al., 2013
[248] Taylor et al., 2011
[249] Grinnell, 2015
[250] Grinnell, 2015
[251] McDonald, 2014
[252] UNDS, 2011
[253] ESF, 2013
[254] GACC, 2014
[255] Pottier, 2013
[256] FAO, 2014
[257] ESF, 2013
[258] UNSD, 2013
[259] FAO, 2010
[260] UNSD, 2011
[261] UNSD, 2013
[262] ESF, 2013
[263] Wang, et al., 2013
[264] Taylor, et al., 2011
[265] ESF, 2013
[266] Grinnell, 2015
[267] Grinnell, 2015
[268] ESF, 2014
[269] ESF, 2014
[270] Grinnell, 2015
[271] WISIONS, 2014
[272] Grinnell, 2015
[273] ESF, 2013
[274] ESF, 2013
[275] ESF, 2013
[276] Grinnell, 2015
[277] Grinnell, 2015
[278] FAO, 2010
[279] Grinnell, 2015
[280] ESF, 2013
[281] ESF, 2013
[282] Pottier, 2013
[283] Pottier, 2013
[284] ESMAP, 2003
[285] Grinnell, 2015
[286] ESMAP, 2003
[287] ESMAP, 2003
[288] Kojima, 2011
[289] Grinnell, 2015
[290] ESF, 2013
[291] ESF, 2013
[292] ESF, 2013
[293] Grinnell, 2015
[294] ESF, 2013
[295] Wang et al., 2013
[296] Wang et al., 2013
[297] Grinnell, 2015

[298] Grinnell, 2015
[299] WISIONS, 2014
[300] GACC, 2013
[301] Grinnell, 2015
[302] Grinnell, 2015
[303] WLPGA, 2014
[304] PBR, 2015
[305] GACC, 2014c
[306] Accenture, 2011
[307] NBS Nigeria, 2015
[308] NIAF, 2013
[309] Accenture, 2011
[310] GACC, 2014c
[311] Onuvae, 2015
[312] Accenture, 2011
[313] PBR, 2015
[314] PBR, 2015
[315] NIAF, 2013
[316] FAO, 2010
[317] Accenture, 2011
[318] Butler, 2005
[319] Terminski, 2012
[320] Hugo 2010
[321] World Bank, 2015
[322] Accenture, 2011
[323] Accenture, 2011
[324] Accenture, 2011
[325] IEA, 2014
[326] Afrane & Ntiamoah, 2011
[327] Ecoinvent, 2010
[328] Afrane & Ntiamoah, 2011
[329] GACC, 2014c
[330] Accenture, 2011
[331] NBS Nigeria, 2015
[332] NIAF, 2013
[333] GACC, 2014c
[334] Onuvae, 2015
[335] Accenture, 2011
[336] NIAF, 2013
[337] UNSD, 2011
[338] OECD/FAO, 2014
[339] FAO, 2014
[340] Accenture, 2011
[341] NBS Nigeria, 2015
[342] NIAF, 2013
[343] GACC, 2014c
[344] FAO, 2010
[345] Accenture, 2011
[346] NBS Nigeria, 2015
[347] NIAF, 2013
[348] GACC, 2014c
[349] UNSD, 2011
[350] Onuvae, 2015
[351] Accenture, 2011
[352] Accenture, 2011
[353] NIAF, 2013

[354] Accenture, 2011
[355] IEA, 2014
[356] Accenture, 2011
[357] Accenture, 2011
[358] ESMAP, 2007
[359] ESMAP, 2004
[360] ESMAP, 2007
[361] ESMAP, 2004
[362] ESMAP, 2004
[363] Accenture, 2011
[364] Accenture, 2011
[365] Accenture, 2011
[366] BTG, 2010
[367] FAO, 2010
[368] Accenture, 2011
[369] Accenture, 2011
[370] UNSD, 2011
[371] Accenture, 2011
[372] GACC, 2014c
[373] Schlag & Zuzarte, 2008
[374] ESMAP, 2004
[375] Accenture, 2011
[376] ESMAP, 2007
[377] Accenture, 2011
[378] ESMAP, 2004
[379] ESMAP, 2004
[380] Accenture, 2011
[381] ESMAP, 2007
[382] ESMAP, 2007
[383] Accenture, 2011
[384] ESMAP, 2004
[385] ESMAP, 2004
[386] Accenture, 2011
[387] WLPGA, 2014
[388] NIAF, 2013
[389] ESMAP, 2004
[390] UNSD, 2011
[391] ESMAP, 2004
[392] Accenture, 2011
[393] Project Gaia, 2015
[394] GACC, 2013
[395] Solar Sister, 2014
[396] Accenture, 2012b
[397] Accenture, 2012b
[398] World Bank, 2015
[399] FAO, 2010
[400] Accenture, 2012b
[401] Accenture, 2012b
[402] Sarpong, 2015
[403] IEA, 2014
[404] Accenture, 2012b
[405] Afrane & Ntiamoah, 2011
[406] Afrane & Ntiamoah, 2011
[407] GACC, 2014c
[408] Accenture, 2012b
[409] ECG, 2014

[410] Sarpong, 2015
[411] Accenture, 2012b
[412] Sarpong, 2015
[413] Sarpong, 2015
[414] FAO 2010
[415] UNSD, 2011
[416] Accenture, 2012b
[417] OECD/FAO, 2014
[418] Sarpong, 2015
[419] UNSD, 2011
[420] Accenture, 2012b
[421] Matthews & Zeissig, 2011
[422] ECG, 2014
[423] Accenture, 2012b
[424] Accenture, 2012b
[425] Accenture, 2012b
[426] Accenture, 2012b
[427] Accenture, 2012b
[428] Accenture, 2012b
[429] World Bank, 2012
[430] World Bank, 2012
[431] WLPGA, 2014
[432] Accenture, 2012b
[433] Accenture, 2012b
[434] Sarpong, 2015
[435] Sarpong, 2015
[436] Sarpong, 2015
[437] WLPGA, 2014
[438] WLPGA, 2014
[439] WLPGA, 2014
[440] World Bank, 2012
[441] Sarpong, 2015
[442] BTG, 2010
[443] FAO, 2010
[444] Accenture, 2012b
[445] FAO, 2010
[446] FAO, 2010
[447] Sarpong, 2015
[448] Sarpong, 2015
[449] Sarpong, 2015
[450] Schlag & Zuzarte, 2008
[451] ESMAP, 2011
[452] Edjekumhene et al., 2007
[453] World Bank, 2012
[454] Neufeldt et al., 2015
[455] Sarpong, 2015
[456] ESMAP, 2011
[457] Sarpong, 2015
[458] ESMAP, 2011
[459] Edjekumhene et al., 2007
[460] Arthur et al., 2011
[461] World Bank, 2012
[462] Blackden & Wodon, 2006
[463] Sarpong, 2015
[464] Blackden & Wodon, 2006
[465] Sarpong, 2015

[466] World Bank, 2012
[467] Neufeldt et al., 2015
[468] Neufeldt et al., 2015
[469] Neufeldt et al., 2015
[470] Sarpong, 2015
[471] Westenhaus, 2012
[472] GACC, 2013
[473] UNEP, 2013
[474] ASTAE, 2013
[475] WLPGA, 2014
[476] Sarpong, 2015
[477] Sarpong, 2015
[478] BTG, 2010
[479] ESMAP, 2006
[480] World Bank, 2012
[481] GVEP International, 2012a
[482] FAO, 2010
[483] GVEP International 2013
[484] GVEP International, 2012a
[485] UNDP 2013
[486] UNDP 2013
[487] Terminski 2012
[488] GVEP International, 2012a
[489] GVEP International, 2012a
[490] GVEP International, 2012a
[491] IEA, 2014
[492] Pennise et al., 2001
[493] Afrane & Ntiamoah, 2011
[494] GACC, 2014c
[495] GVEP International, 2012a
[496] SID, 2015
[497] GACC, 2014c.
[498] GVEP International, 2012a
[499] GACC, 2014c
[500] SID, 2015
[501] Wanjohi, 2015
[502] Wanjohi, 2015
[503] Wanjohi, 2015
[504] Wanjohi, 2015
[505] Ngusale, et al., 2014
[506] UNSD, 2011
[507] FAO, 2014
[508] Ngusale, et al., 2014
[509] UNSD, 2011
[510] GVEP International, 2012a
[511] EAC, 2006
[512] GVEP International, 2012d
[513] Matthews & Zeissig, 2011
[514] GVEP International, 2012a
[515] EnDev, 2012
[516] EnDev, 2012
[517] Djédjé, et al., 2009
[518] GVEP International, 2012a
[519] EAC, 2006
[520] Ngusale, et al., 2014
[521] Versol, 2015

[522] GVEP International, 2012a
[523] GVEP International, 2012a
[524] Stokes, 2015
[525] GVEP International, 2012a
[526] EAC, 2006
[527] GVEP International, 2012a
[528] Njenga, 2014
[529] GVEP International, 2013
[530] Neufeldt et al., 2015
[531] EEP, 2013
[532] GVEP International, 2013
[533] Ngusale et al., 2014
[534] Ngusale et al., 2014
[535] GVEP International, 2013
[536] EEP, 2013
[537] GVEP International, 2012a
[538] Wanjohi, 2015
[539] GVEP International, 2012a
[540] BTG, 2010
[541] GVEP International, 2012a
[542] FAO, 2010
[543] Wanjohi, 2015
[544] Schlag & Zuzarte, 2008
[545] EAC, 2006
[546] Ngusale et al., 2014
[547] Kojima, 2011
[548] Njenga, 2014
[549] GVEP International, 2012d
[550] Kojima, 2011
[551] GVEP International, 2012d
[552] Falzon et al., 2013
[553] Wanjohi, 2015
[554] Wanjohi, 2015
[555] ESMAP, 2007
[556] Wanjohi, 2015
[557] EEP, 2013
[558] UNHCR, 2001
[559] GACC, 2015b
[560] WLPGA, 2014
[561] McPeak, 2002
[562] EAC, 2006
[563] Malla et al., 2011
[564] WLPGA, 2014
[565] AFREA, 2011
[566] Malla et al., 2011
[567] Malla et al., 2011
[568] Wanjohi, 2015
[569] Wanjohi, 2015
[570] Neufeldt et al., 2015
[571] Njenga et al., 2013
[572] GVEP International, 2012a
[573] Wanjohi, 2015
[574] GVEP International, 2012a
[575] GVEP International, 2012a
[576] GACC, 2013
[577] Wanjohi, 2015

[578] Njenga et al., 2013
[579] GVEP International, 2013
[580] GVEP International, 2013
[581] BTG, 2010
[582] Njenga et al., 2013
[583] GVEP International, 2013
[584] GVEP International, 2012a
[585] PRB, 2015
[586] GVEP International, 2013
[587] World Bank, 2015
[588] FAO, 2010
[589] GVEP International, 2012b
[590] GVEP International, 2012b
[591] GVEP International, 2012b
[592] GVEP International, 2012b
[593] BMWi, 2009
[594] Uganda Bureau of Statistics. 2014.
[595] Pennise et al., 2001
[596] Afrane & Ntiamoah, 2011
[597] Energypedia. 2015
[598] GACC, 2014c
[599] Accenture, 2011
[600] NBS Nigeria, 2015
[601] NIAF, 2013
[602] GVEP International, 2012b
[603] GVEP International, 2012b
[604] GACC, 2014c
[605] Wanjohi, 2015
[606] GVEP International, 2012b
[607] Wanjohi, 2015
[608] Wanjohi, 2015
[609] Wanjohi, 2015
[610] Wanjohi, 2015
[611] GVEP International, 2012b
[612] GACC, 2014c
[613] UNSD, 2013
[614] FAO, 2014
[615] FAO, 2010
[616] UNSD, 2011
[617] UNSD, 2013
[618] UNSD, 2011
[619] UNSD, 2013
[620] GVEP International, 2012b
[621] GVEP International, 2012b
[622] GVEP International, 2012b
[623] Black, 2015
[624] GVEP International, 2012b
[625] GVEP International, 2012b
[626] EAC, 2006
[627] Ministry of Water and Environment, 2013
[628] GVEP International, 2012b
[629] Ben-Kalio, 2007
[630] Black, 2015
[631] EEP, 2013
[632] EEP, 2013
[633] Herzog, 2015

[634] GVEP International, 2012b
[635] GVEP International, 2012b
[636] GVEP International, 2012b
[637] GVEP International, 2012b
[638] Wanjohi, 2015
[639] BTG, 2010
[640] Herzog, 2015
[641] Black, 2015
[642] Schlag & Zuzarte, 2008
[643] EEP, 2013
[644] Herzog, 2015
[645] Herzog, 2015
[646] GVEP International, 2012d
[647] Kabarole Research and Resource Centre, 2013
[648] Herzog, 2015
[649] Kabarole Research and Resource Centre, 2013
[650] Kabarole Research and Resource Centre, 2013
[651] EEP, 2013
[652] Black, 2015
[653] GACC, 2015b
[654] Black, 2015
[655] EAC, 2006
[656] GACC, 2015b
[657] GACC, 2015b
[658] Black, 2015
[659] FAO, 2010
[660] FAO, 2010
[661] Blackden & Wodon, 2006
[662] Black, 2015
[663] Kabarole Research and Resource Centre, 2013
[664] Kabarole Research and Resource Centre, 2013
[665] Herzog, 2015
[666] Kabarole Research and Resource Centre, 2013
[667] GACC, 2014c
[668] Herzog, 2015
[669] Herzog, 2015
[670] UNSD, 2011
[671] UNSD, 2011
[672] Herzog, 2015
[673] Kabarole Research and Resource Centre, 2013
[674] GVEP International, 2012c
[675] Ashden, 2009
[676] Wanjohi, 2015
[677] Wanjohi, 2015
[678] GACC, 2013
[679] BTG, 2010
[680] Herzog, 2015
[681] Black, 2015
[682] Herzog, 2015
[683] GVEP International, 2012b