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Life Cycle Assessment of Cooking Fuel Systems in India, China, Kenya, and Ghana

Office of Research and Development
National Risk Management Research Laboratory

Life Cycle Assessment of Cookstoves and Fuels in India, China, Kenya, and Ghana

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NOTICE

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ABSTRACT

Daily use of traditional cooking fuels and stoves in India, China, Kenya, and Ghana emits harmful air pollutants that result in over a million premature deaths annually. Reducing pollution from cookstoves is a key priority, as emissions from traditional cookstoves and open fires with solid fuels are a major health concern and yield numerous environmental impacts. This project is being conducted by the U.S. Environmental Protection Agency (US EPA) that aims to provide life cycle assessment (LCA) data and tools that inform decisions regarding cookstove use and fuel selection. This research expands the geographic scope of the Phase I study to include both Kenya and Ghana. This work phase developed new stove use emission life cycle inventories (LCIs) to conduct an uncertainty analysis for each fuel and stove type combination. The current study also performs sensitivity analyses that test the effect of stove thermal efficiency, stove technology use, electrical grid mix, forest renewability factor, and allocation approach on environmental impacts of cookstove use. The study quantifies the effect that potential shifts in the cooking fuel mix may have on the environmental impact of delivered cooking energy.

A normalized presentation of results is provided for each country, which helps to identify the categories of environmental impact that are most strongly linked to the cooking sector. Study results reinforce the findings of the Phase 1 study supporting the observation that the use of traditional fuels and cookstoves contributes disproportionately to the environmental footprint of cooking in developing nations. Normalized results further indicate that the cooking sector is a dominant contributor for the countries of focus to national particulate matter formation potential and black carbon (BC) and short-lived climate pollutant impacts, which are the two LCA categories most strongly linked to human health impacts.

The study quantitatively demonstrates through the application of LCA that both cooking fuel mix substitutions and stove technology upgrades provide promising avenues for reducing particulate matter and BC emissions. India's results show that continued reliance on crop residue and dung contributes disproportionately to particulate matter and BC environmental impacts. The results suggest that a major environmental benefit in China could be realized by promoting cooking fuel mix substitutions or stove technology improvements to replace the combustion of coal powder in traditional stoves. Kenya and Ghana would benefit from adoption of improved stove designs for both firewood and charcoal fuel. Use of improved charcoal kiln technology also has the potential to significantly reduce the impact of charcoal use and production.

The study demonstrates the positive relative environmental results associated with liquefied petroleum gas (LPG) and natural gas, which show a tendency to shift environmental burdens away from indoor air pollutants and to other impact categories such as fossil fuel depletion, fresh water eutrophication, and terrestrial acidification potential when substituted for traditional fuels. Electric cookstoves demonstrate positive environmental performance in both Kenya and Ghana, where they are characterized by relatively clean electrical grids. Without a reduction in reliance on the use of coal as a source of electrical energy in India and China, electric cookstoves are not able to match the environmental performance of other modern cooking fuels. In addition to the selection of results presented in this report, dynamic results workbooks are available to customize selection of national cooking fuel mix, stove technology use, and sensitivity parameters to support the analysis of potential effects on environmental impacts to support cookstove policy development in India, China, Kenya, and Ghana.

FOREWORD

The United States Environmental Protection Agency (U.S. EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) within the Office of Research and Development (ORD) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication was produced in support of ORD’s Air, Climate, and Energy FY16-19 Strategic Research Action Plan. EPA, along with other federal partners, is working in collaboration with the Global Alliance for Clean Cookstoves to conduct research and provide tools to inform decisions about clean cookstoves and fuels in developing countries. EPA previously completed a life cycle assessment (LCA) comparing the environmental footprint of current and potential fuels and fuel mixes used for cooking within India and China (Cashman et al. 2016). This study furthers the initial work by expanding the LCA methodology to include new cooking mix and electrical grid scenarios, additional sensitivity analyses, uncertainty analyses, and includes a normalized presentation of results. This phase of work also expands the geographic scope of the study to include both Kenya and Ghana. Study results will allow researchers and policy-makers to quantify sustainability-related metrics from a systems perspective.

Cynthia Sonich-Mullin, Director
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TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF TABLES

Page

LIST OF TABLES (Continued)

Page

LIST OF FIGURES

Page

LIST OF FIGURES (Continued)

Page

LIST OF FIGURES (Continued)

Page

ACRONYMS AND ABBREVIATIONS

AD	Anaerobic Digester
AGB	Above Ground Biomass
AIS	Accelerated Improvement Scenario
BAU	Business As Usual
BC	Black Carbon
BCG	Boston Consulting Group
BGB	Below Ground Biomass
BrC	Brown Carbon
CCS	Carbon Capture and Storage
CED	Cumulative Energy Demand
CFC	Chlorofluorocarbons
CH_4	Methane
CIS	Continued Improvement Scenario
CN	China
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_3	Carbonate
DME	Dimethyl Ether
DS	Domestic Supply
EC	Elemental Carbon
eq	Equivalent emissions
EIA	Energy Information Administration
EOL	End of Life
ERG	Eastern Research Group
FAO	Food and Agriculture Organization
FC	Final Consumption
FEP	Freshwater Eutrophication Potential
FDP	Fossil Fuel Depletion
GACC	Global Alliance for Clean Cookstoves
GCCP	Global Climate Change Potential
GDP	Gross Domestic Product
GH	Ghana
GHG	Greenhouse Gas
GJ	Gigajoule
GSF	Gold Standard Foundation
HAPs	Hazardous Air Pollutants
HHV	Higher Heating Value
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle

ACRONYMS AND ABBREVIATIONS

IN	India
IOCL	Indian Oil Corporation Limited
IPCC	Inter-Governmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
kg	Kilogram(s)
LBNL	Lawrence Berkeley National Laboratory
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
LHV	Lower Heating Value
ISO	International Standards Organization
K	Potassium
KE	Kenya
LPG	Liquefied Petroleum Gas
N	Nitrogen
NGCC	Natural Gas Combined Cycle
NH_3	Ammonia
NMVOC	Non-Methane Volatile Organic Compound
NOx	Nitrogen Oxides
NO_3	Nitrate
N_2O	Nitrous Oxide
NPK	Nitrogen, Phosphorus and Potassium
NREL	National Renewable Energy Laboratory
NRMRL	National Risk Management Research Laboratory
OC	Organic Carbon
ODP	Ozone Depletion Potential
ONGC	Oil and Natural Gas Corporation
ORD	Office of Research and Development
P	Phosphorus
POFP	Photochemical Oxidant Formation Potential
$PM_{2.5}$	Particulate Matter, ≤2.5 micrometers
PMFP	Particulate Matter Formation Potential
PM10	Particulate Matter, ≤10 micrometers
QA	Quality Assurance
QAPP	Quality Assurance Project Plan
SI	Supplementary Information
SLCPs	Short-Lived Climate Pollutants
SO_2	Sulfur Dioxide

ACRONYMS AND ABBREVIATIONS

SOx	Sulfur Oxides
TAP	Terrestrial Acidification Potential
TERI	The Energy and Resources Institute
U.S. EPA	United States Environmental Protection Agency
USDA	United States Department of Agriculture
US LCI	United States LHCFCife Cycle Inventory
VOC	Volatile Organic Carbon
WDP	Water Depletion Potential
WISDOM	Woodfuel Integrated Supply/Demand Overview Mapping

ES.1 EXECUTIVE SUMMARY

ES.1.1 Introduction

Cookstove use in developing countries affects millions of lives daily with far-reaching consequences. Reducing pollution from cookstoves is a key priority as emissions from cookstoves and open fires with solid fuels are a major health concern and contribute to numerous environmental impacts. The U.S. Environmental Protection Agency (U.S. EPA) is conducting research to provide data and tools that inform decisions regarding clean cookstoves and fuels for developing countries. Toward this end, the U.S. EPA previously completed a life cycle assessment (LCA) comparing the environmental footprint of current and potential fuels and cooking fuel mixes used for cooking within India and China (Cashman et al. 2016). This report builds on the original India and China cookstove LCA (referred to throughout this report as the "Phase I study"), by expanding the LCA methodology to include new cooking fuel mix and electrical grid scenarios, additional sensitivity analysis, uncertainty analysis, and a normalized presentation of results. This phase of work also expands the geographic scope of the study to include both Kenya and Ghana.

The scope expansion of the Phase II work was conducted to develop new data on stove combustion emissions and present uncertainty results so that policies aimed at reduction of environmental impacts in the cooking sector can be pursued with greater confidence. Implementation of sensitivity analyses regarding stove thermal efficiency, cooking fuel mix, electrical grid mix, forest renewability, and the choice of LCA allocation approach further bolster the ability of the research to provide robust guidance tools to stakeholders considering changes to the current cooking fuel mix and stove technology for the countries studied.

To support decision-making the study focuses on delivering information to stakeholders such as insights into the potential variation in emissions associated with a given stove type (e.g., firewood burned in a traditional stove), the potential benefits of adopting improved stove designs or implementing specific cooking fuel mix substitutions (e.g., charcoal replaces crop residue), and the influence that renewability of forestry practice has on global climate change potential (GCCP) of wood-based cooking fuels.

ES.1.2 Phase II Project Approach

The Phase II report is intended to provide an understanding of the types of data and other information resulting from the use of LCA to evaluate fuels and stoves for India, China, Kenya, and Ghana. Plans are to develop a LCA calculator that provides access to all of the data and information available through this research. This will allow for a site-specific analysis to evaluate LCA environmental tradeoffs by stakeholders interested in furthering emission reductions for this source category (i.e., emissions from the wide array of stoves and fuels).

The number of countries and the breadth of included cooking fuels, stove types, fuel mixes, and sensitivity analysis prohibits the possibility of including or discussing all generated results within the report itself. Rather, the Phase II report is intended to document pertinent methods regarding study assumptions and present select results that provide the most comprehensive and engaging perspective on the findings of the second phase of work. A series of four dynamic results workbooks is included along with detailed supplementary information (SI) files that comprehensively document the full range of research, tabular results, and figures that were generated for Phase II. Table 1-1 in the main report introduces the associated supplementary files, while Section 4.7 presents an introduction to results as presented both in this report and in the associated results workbooks for each country.

Detailed discussion and figure presentation in the main report focuses on the following impact categories:

- GCCP
- Cumulative Energy Demand (CED)
- Particulate Matter Formation Potential (PMFP)
- Black Carbon (BC) and Short-Lived Climate Pollutant Potential.

Results for other impact categories are presented when the findings are of particular interest or the results do not follow the same trends as seen for the four primary impact categories.

ES.1.3 Methodology

This LCA investigates both current fuels and those with market potential for cookstoves in India, China, Kenya, and Ghana. The current national cooking fuel mix for each country, including potential fuels considered but not currently utilized in measurable quantities, is illustrated in Figure ES-1. The Phase II report focuses on the environmental impact of cooking fuels included in both current and projected future cooking fuel mixes along with select results from the sensitivity analysis that highlight key national trends. The following life cycle stages are analyzed for each fuel system:

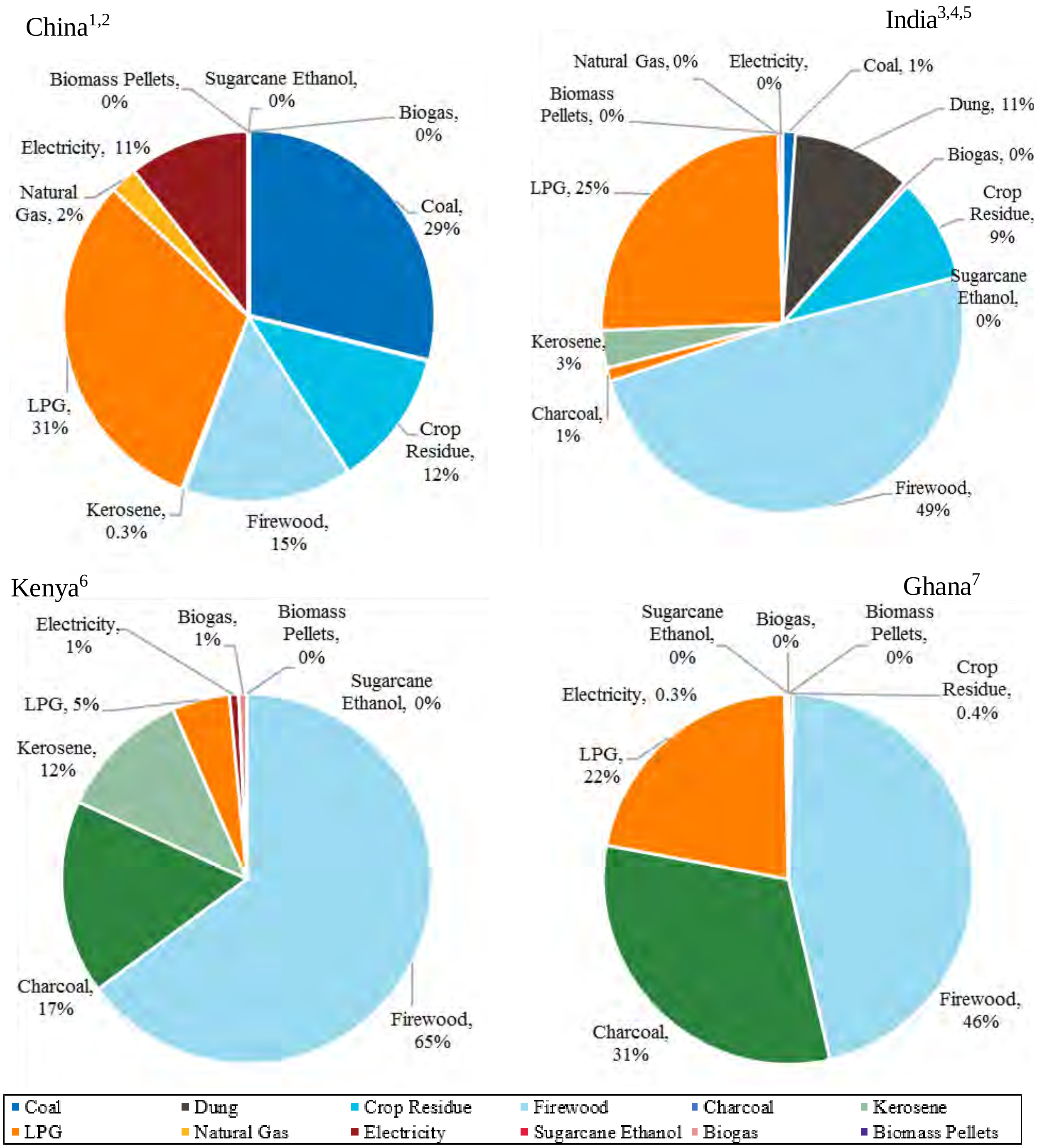
- **Production** of the cookstove fuel feedstock, including all stages from extraction or acquisition of the fuel feedstock from nature through production into a form ready for processing into cooking fuel (e.g., cultivation and harvesting of sugarcane, extracting crude oil from wells).

- **Processing** of the fuel into a form ready to be used in a cookstove.

- **Distribution** of fuels from the production site to the processing location and on to a retail location or directly to the consumer. Distribution also includes bottling for fuels stored in cylinders.

- **Use** of the fuel via combustion of the fuel or use of electricity in a cookstove, including disposal of any combustion wastes or residues (e.g., ash).

Cookstove production and distribution, human energy expended during collection of fuels, and the production, preparation, consumption, and disposal of food and food wastes are outside the boundaries of this project. A previous LCA examining production of fuel-efficient cookstoves found that the use phase significantly dominates life cycle greenhouse gas (GHG) emissions regardless of the combusted cooking fuel type utilized (Wilson 2016); therefore, it is reasonable to exclude processes associated with stove production and distribution from the study scope.



Sources: [1]Dalberg 2014, [2]NBSC 2008, [3]Dalberg 2013b, [4]Gov. of India 2014, [5]Venkataraman et al. 2010, [6]KNBS 2012, [7]GLSS6 2014

Figure ES-1. Current cooking fuel mix in China, India, Kenya, and Ghana.

Results of the LCA are expressed in terms of a common functional unit. As this analysis is a comparison of different fuels used to provide cooking energy, an energy functional unit is a proper basis of comparison. Therefore, the LCA results are based on useful energy delivered for cooking: ***1 gigajoule (GJ) of useful energy delivered to the pot for cooking***.

This study investigates bio-based and fossil-based cooking fuels, as well as electricity (a mix of fuel types) currently used at a measurable level of capacity in India, China, Kenya, and Ghana, as depicted in Figure ES-1. Cooking fuels not currently used or used in only small quantities but with future market potential in these four countries are also assessed. Four future cooking fuel mix scenarios were developed for each nation studied (displayed in Table 3-6, Table 3-8, Table 3-10, and Table 3-12 of Section 3.1 of the main report) through review of public sources discussing possible changes in the fuels used within these countries, as well as through an analysis of past trends observed within the four study countries. The scenarios focus on a continuation of current trends, feasible substitution of modern and improved fuels, and a Diverse Modern Fuels scenario for each nation that explores a more dramatic departure from the current cooking fuel mix.

National estimates of stove technology use were developed for each country and are applied to both current and future cooking fuel mixes. A future improved stove technology mix that assumes full adoption of improved stove designs is included in the analysis and serves to highlight the relative potential environmental benefit of stove technology upgrades both in combination with and as opposed to a strategy that focuses on cooking fuel mix substitutions. Adoption refers to the future use of improved stove technologies or fuel forms in place of current alternatives. Each stove group, which is defined as a unique combination of fuel type, stove type (traditional, improved, modern) and country of use, has an associated current and future improved stove thermal efficiency value based on records of stove performance drawn from the literature. Results are run for both estimates of stove thermal efficiency to estimate the current potential variability that exists within each stove group. Impact results for electric cookstoves are generated for both current and potential future electrical grid mix scenarios.

Two forms of methodology-related sensitivity analysis are also included within the study. The first of these involves the choice of LCA modeling conventions that are used to allocate environmental impact among multi-output processes. The effect of allocation approach selection on environmental impact of cooking with crop residue, biogas, and sugarcane ethanol are explored in the sensitivity analysis. Table 3-14 lists both the baseline and sensitivity allocation approaches considered in this study, and Section 3.3 describes each method in detail. The second methodology-related sensitivity involves the national forest renewability factor that is used to estimate GHG emissions for each country. Table 4-1 lists both Phase I and Phase II forest renewability factors considered in the sensitivity analysis. As is described in Section 4.1, for biomass, only carbon dioxide (CO_2) emissions from non-renewable wood products are considered to contribute to GCCP.

Uncertainty results were calculated using baseline assumptions for each stove grouping. Uncertainty ranges help to quantify variability in the environmental performance of a given stove grouping and to demonstrate the potential overlap in environmental performance that exists between stove groupings. The nature of this study, which looks at national average environmental emissions of numerous cookstove options, necessarily encompasses many sources of uncertainty that affect result calculations at various levels of implementation, which range from consideration of a single life cycle stage for a given fuel all the way up to aggregate national cooking sector results. Section 4.5 introduces Monte Carlo uncertainty analysis and the study parameters that contribute to uncertainty in baseline results.

The Phase II study also includes a normalized presentation of life cycle impact assessment (LCIA) results for each country. Normalization compares cooking sector impacts to national estimates of characterized environmental impact in each country. Normalized results provide an indication of the relative contribution that the cooking sector makes to environmental impact across the different categories considered in this study. Section 4.6 describes normalization and documents the country-specific statistics and normalization factors that were used in the analysis.

The environmental analysis was conducted in accordance with the following voluntary international standards for LCAs:

- International Standards Organization (ISO) 14040: 2006, Environmental management – Life cycle assessment – Principles and framework (ISO 2010a); and
- ISO 14044: 2006, Environmental management – Life cycle assessment – Requirements and guidelines (ISO 2010b).

The majority of life cycle inventory (LCI) data were extracted from existing studies in publicly available academic literature. An LCI is an accounting of the material, energy, and water inputs and the product, waste, emission, and water outputs for a product or process (Baumann and Tillman 2004). Detailed unit process LCI data were entered into openLCA software (GreenDelta 2016) to calculate the LCIA results. LCIA is the process of translating emissions data contained in an LCI into environmental loads, which help users to interpret cumulative environmental impacts of the studied system (Baumann and Tillman 2004). Table ES-1 lists ten impact assessment indicators included in this study and the units in which they are reported.

Table ES-1. LCIA Categories Considered in Phase II

Impact/Inventory Category	Abbreviation	Unit
Global Climate Change Potential	GCCP	kg CO_2 eq
Cumulative Energy Demand	CED	MJ
Water Depletion Potential	WDP	m^3
Black Carbon and Short-Lived Climate Pollutants	BC	kg BC eq
Particulate Matter Formation Potential	PMFP	kg PM_{10} eq
Terrestrial Acidification Potential	TAP	kg SO_2 eq
Freshwater Eutrophication Potential	FEP	kg P eq
Photochemical Oxidant Formation Potential	POFP	kg NMVOC eq
Ozone Depletion Potential	ODP	kg CFC-11 eq
Fossil Depletion Potential	FDP	kg oil eq

This suite of indicators addresses global, regional, and local impact categories of relevance to the cookstove sector such as energy demand driving depletion of bio-based and fossil-fuel resources, and GHG and BC emissions causing both long-term and short-term climate effects. Of particular concern, are those impact categories that directly impact human health.

These categories include emissions resulting in BC, particulate matter formation, and photochemical oxidant formation, all of which can lead to eye irritation, respiratory disease, increased risk of infection, and cancer (Goedkoop et al. 2008). Table 1-4 in Section 1.3.8 provides a description of each impact category. Results for most impact categories are calculated using the ReCiPe impact assessment methodology (Goedkoop et al. 2008). For the category of GCCP, contributing elementary flows are characterized using factors reported by the Intergovernmental Panel on Climate Change (IPCC) in 2013 with a 100-year time horizon (IPCC 2013). BC and co-emitted species are characterized to BC–equivalents (eq) based on a novel method released by the Gold Standard Foundation (GSF) (GSF 2015). CED and WDP are also included as inventory indicators. CED and WDP inventory indicators are not associated directly with environmental impacts but rather provide a cumulative count of energy and water resources used within the study system. CED includes both renewable and non-renewable energy sources.

ES.1.4 Key Findings

Select LCA results pertaining to cooking fuel mix scenarios for each country, which include the potential effect of improved stove technology adoption, are presented in Figure ES-2, Figure ES-3, Figure ES-4, and Figure ES-5 for India, China, Kenya, and Ghana, respectively. Potential future cooking fuel mix results in each figure are presented relative to current fuel mix impacts for both GCCP and PMFP. Section 3.1 introduces the developed projections for future cooking fuel mix scenarios.

One of the more positive findings of the Phase II work involves the discovered sensitivity of BC and PMFP impact to projected changes in both stove technologies use and cooking fuel mix substitutions. This finding is clearly demonstrated in Figure ES-2 through Figure ES-5 for PMFP by the dramatic drop in bar height associated with all potential future cooking fuel mix scenarios, relative to the current cooking fuel mix scenario. This finding indicates that multiple policy approaches can be expected to produce desirable results concerning the two impact categories that are most strongly affected by activity in the cooking sector. All four nations still rely not only on traditional cooking fuel sources but also on traditional cookstoves with low associated thermal efficiencies. Uncertainty results, presented as part of the sensitivity analysis, support findings from the baseline results asserting the significance of emission reductions achievable through adoption of improved stove designs and cooking fuel forms. The term fuel form recognizes that energy feedstocks are not limited to use in just a single configuration. As an example, coal powder can be compressed into honeycomb briquettes or transformed into coal gas, leading to variable environmental performance from a single energy source.

Cooking fuel mixes also demonstrate that in many cases the magnitude of impact for a given country and indicator tends to be driven predominantly by one or two traditional fuels and stove technologies. For example, PMFP emissions in India are disproportionately associated with dung and crop residue combustion, and the use of these two fuels for cooking is exacerbated by reliance on traditional stoves. In China, reliance on various forms of coal to provide approximately one-third of cooking energy produces a disproportionate share of impact in several impact categories. Traditional cooking fuel sources are associated with a wide range of stove types and even fuel forms, and the results shown present an opportunity to reduce environmental burdens without the necessity of abandoning a traditional fuel source. Substituting honeycomb coal briquettes for coal powder in China, for example, presents an opportunity to reduce GCCP and PMFP impacts of coal-derived cooking energy by approximately 70 and 97 percent, respectively.

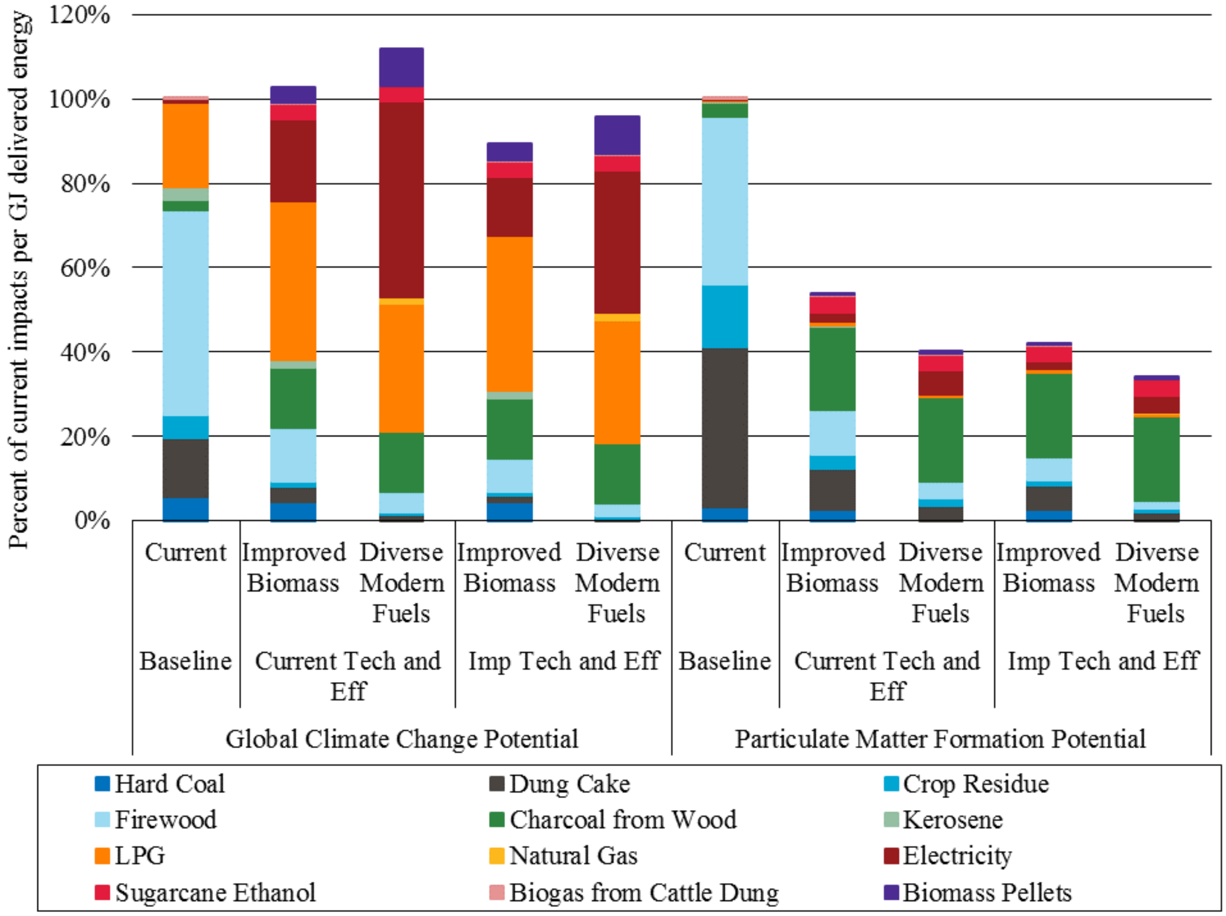


Figure ES-2. Select fuel mix LCIA results for GCCP and PMFP under varying technology assumptions in India. Scenario results shown relative to baseline results.

(Axis abbreviations: Tech=stove technology, Eff=stove efficiency, Imp=improved)

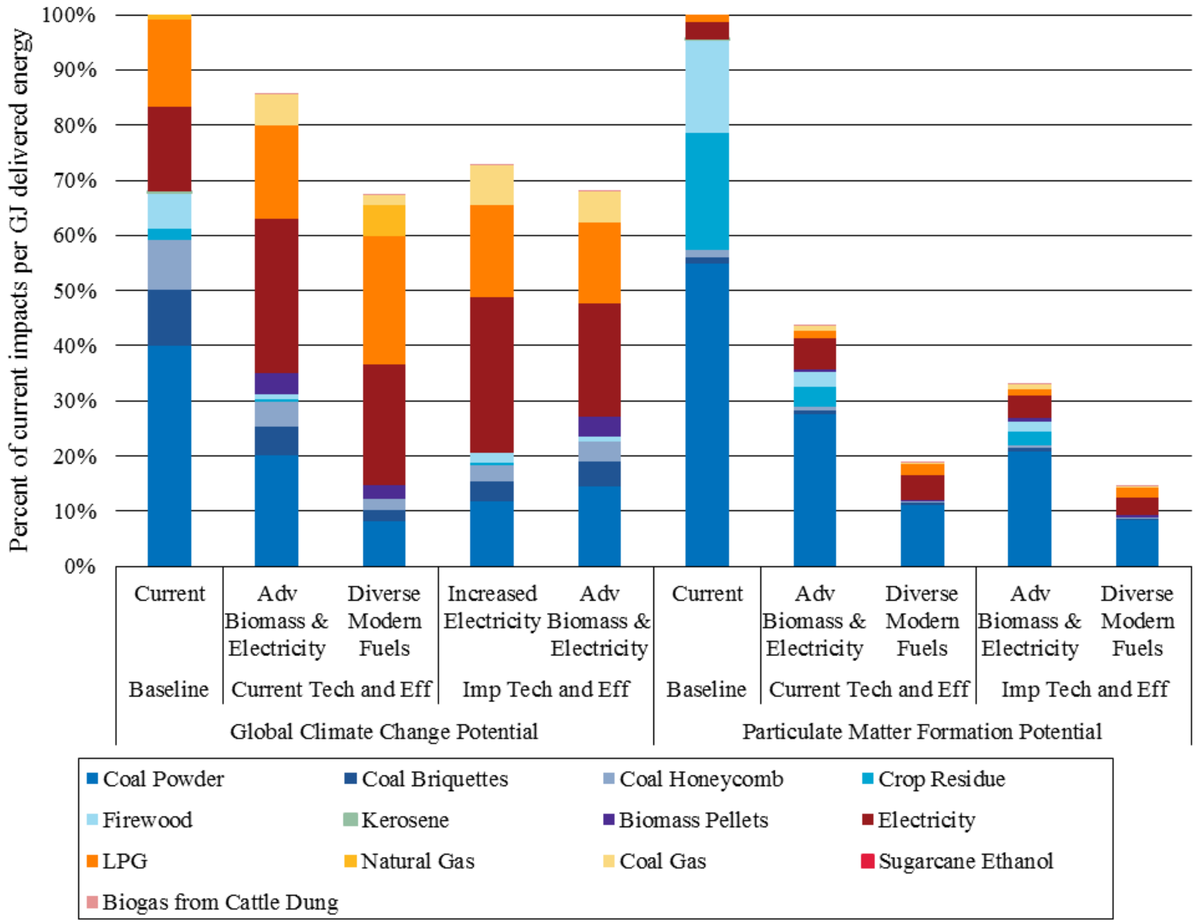


Figure ES-3. Select fuel mix LCIA results for GCCP and PMFP under varying technology assumptions in China. Scenario results shown relative to baseline results.

(Axis abbreviations: Adv=Advanced, Tech=stove technology, Eff=stove efficiency, Imp=improved)

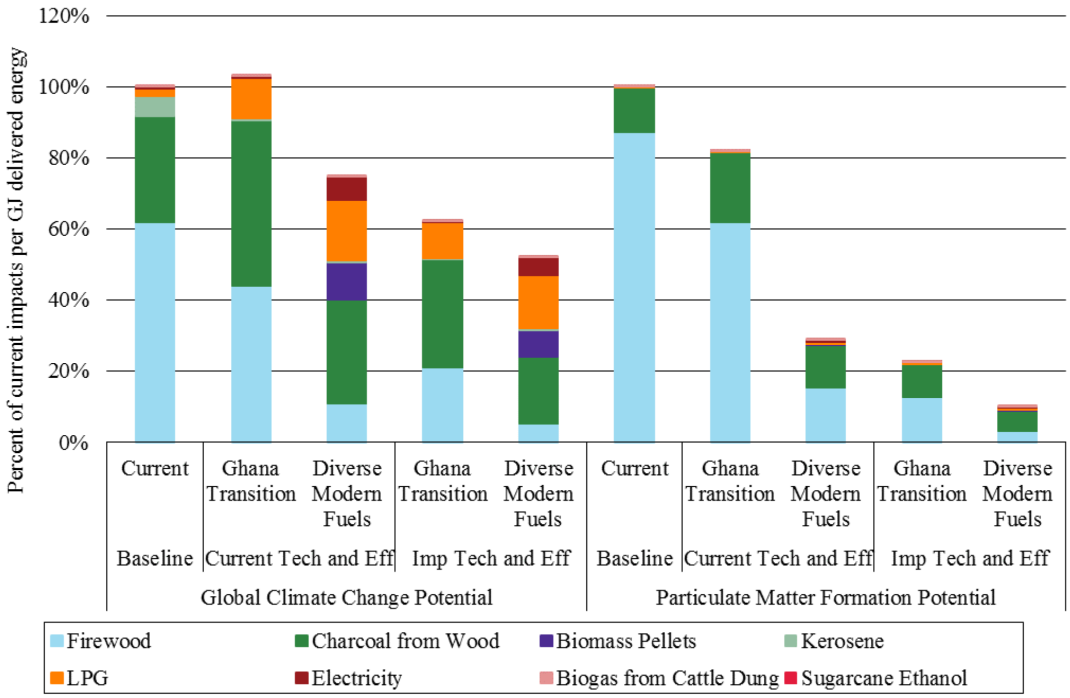


Figure ES-4. Select fuel mix LCIA results for GCCP and PMFP under varying technology assumptions in Kenya. Scenario results shown relative to baseline results.
(Axis abbreviations: Tech=stove technology, Eff=stove efficiency, Imp=improved)

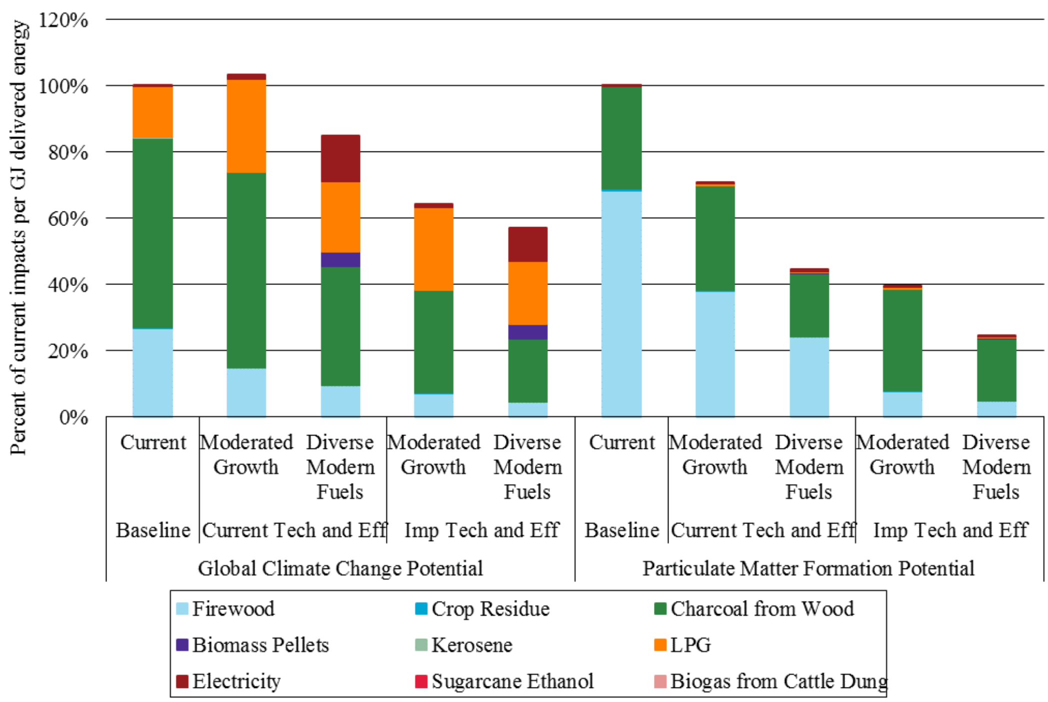


Figure ES-5. Select fuel mix LCIA results for GCCP and PMFP under varying technology assumptions in Ghana. Scenario results shown relative to baseline results.
(Axis abbreviations: Tech=stove technology, Eff=stove efficiency, Imp=improved)

ES.1.4.1 Findings Common to all Countries Studied

While the LCA results' values differ for all country and fuel combinations, certain trends were found to be common across all four countries studied:

- Normalized results for all countries show that BC and PMFP impact categories are strongly linked to the cooking sector. Results also show that impacts in these two categories are sensitive to the projected future fuel mix and stove technology shifts considered in this study, indicating multiple pathways by which to reduce impacts attributable to the cooking sector.

- Utilization of modern cooking fuels such as liquefied petroleum gas (LPG), natural gas, biomass pellets, and ethanol resulted in significant reductions in PMFP and BC, categories strongly linked to the cooking sector.

- Normalized results confirm that traditional fuels pose a significant risk to human health (e.g., due to PMFP). The possibility of using renewably sourced wood fuel in combination with the adoption of improved or pelletized stoves could significantly reduce hazardous emissions while still allowing the use of traditional biomass resources.

- The sensitivity analysis shows that a significant range in potential environmental impact exists between the worst and best performing cookstoves within a given stove type (e.g. firewood traditional).

- Biogas and biomass pellets hold significant potential to reduce household air emissions attributable to the cooking sector.

- Updated LCI information for the agricultural production of sugarcane indicates significant upstream environmental impacts associated with ethanol production.

Findings unique to each country studied are highlighted in the subsequent sections.

ES.1.4.2 India

- Normalized BC impacts in India are high relative to other nations and are disproportionately influenced by the use of dung and crop residues in the current cooking fuel mix.

- The current, coal heavy electricity mix in India and high electrical grid losses contribute to the poor performance of electric cookstoves relative to other modern fuel options.

- Realizing further GCCP impact reductions will be a challenge for India as the country moves to adopt modern fossil-based cooking fuels. GCCP of the current Indian cooking fuel and stove technology mix is at minimum 35 percent lower than that realized by the other nations studied due to a continued reliance on biomass fuels, relatively high baseline forest renewability, and an absence of significant contributions from stoves that exhibit particularly poor performance such as traditional coal powder and charcoal cookstoves, which drive up GCCP impact in the other countries.

ES.1.4.3 China

- The one-third of cooking fuel energy that is produced from coal disproportionately contributes to normalized PMFP and BC impacts in China. Potential reductions in environmental impact realized by switching from coal powder to advanced forms of coal consumption such as honeycomb briquettes or coal gas provide a robust option for consistently improving performance of the cooking sector across all impact categories.

- The current coal-heavy electricity mix in China results in poor performance of electric cookstoves for most impact categories assessed relative to other modern fuel options. Upgrades to China's electricity sector will be required for electric cookstoves to achieve environmental impact scores in line with, or better than, other modern fuels.

ES.1.4.4 Kenya

- Scenario results show that reductions in Kenyan cooking sector emissions, compared to other countries studied, are more sensitive to adoption of improved stove technologies and thermal efficiencies, when holding cooking fuel mix constant. This is because Kenya currently relies heavily on three-stone fires and traditional wood stoves, which are associated with low thermal efficiencies and notable air emissions during cookstove use.

- Forest renewability is important in determining if the best performing wood-based options, biomass pellets and improved firewood stoves, can compete with the GCCP of modern liquid and gas fuel options. This is especially true for Kenya, which has the lowest forest renewability among the four study nations.

- Low availability of renewable wood resources in Kenya indicates that following Ghana's lead in pursuing increased charcoal use as a means of improving urban air quality could lead to significant pressure on other environmental impact categories and forest resources. While charcoal may serve to reduce emissions in the household, it does not reduce cumulative emissions across the supply-chain and serves as an inefficient use of forest resources.

- The current electricity grid in Kenya has the lowest GCCP of all nations studied due to the prevalence of hydropower and geothermal energy in their electrical grid mix. The electricity grid sensitivity results show that all the future electrical grid mixes yield further reductions in GCCP. However, Kenya currently has the lowest national electrification rate, 23 percent (World Bank 2012). of any of the four countries studied, which poses a challenge for use of electric cookstoves.

ES.1.4.5 Ghana

- Ghana demonstrates the second highest sensitivity to improvements in stove technology and efficiency, following Kenya, indicating the potential to reduce cooking sector emissions even in the absence of fuel mix shifts.

- Of the four study nations, Ghana is most heavily reliant on charcoal energy as a source of cooking fuel (GLSS6 2014). Significant improvements in environmental performance are possible through improved charcoal stove and kiln technology adoption. However, even assuming the most optimistic adoption of charcoal technology, this fuel demonstrates consistently poor environmental performance relative to other cooking options and places a heavy burden on forest resources.

- Normalized CED of Ghana’s cooking sector is significantly higher than that realized for other nations, which is due largely to inefficient energy conversion in charcoal kilns and the LPG refining process, as well as lower overall national per capita energy consumption for all sectors compared to national per capita energy use in the other study countries.

Results presented in this report are only a subset of the full results available in the supporting files and were selected to highlight key trends while serving as a guide for interpreting the accompanying result workbooks.

ES.1.5 Report Organization

The remainder of this report is organized as follows:

- **Section 1: Goal and Scope Definition –** Discusses the overall study goal, scope, and boundaries, and describes the LCIA categories addressed in the study.

- **Section 2: Cooking Fuel and Stove Descriptions and Methodology –** Describes details of the cooking fuel LCI models and documents cookstove efficiency, national stove technology use, and sources of emissions information.

- **Section 3: Methodology for Scenario Development and Sensitivity Analysis –** Describes cooking fuel and electrical grid mix scenario development and allocation approaches used within the sensitivity analysis.

- **Section 4: Methodology for Results Compilation –**Provides documentation of LCA methodology-related modeling choices, sensitivity analysis, and results presentation.

- **Section 5: Updated LCA Results for India –** Presents selected LCA results and discussion for India.

- **Section 6: Updated LCA Results for China –** Presents select LCA results and discussion for China.

- **Section 7: LCA Results for Kenya –** Presents select LCA results and discussion for Kenya.

- **Section 8: LCA Results for Ghana –** Presents select LCA results and discussion for Ghana.
- **Section 9: Key Takeaways by Country and Study Conclusions –** Presents a brief summary of key findings specific to each country and highlights trends observed both across and between nations.
- **Section 10: References –** Lists references used in this LCA.
- **Appendix A: Baseline Single Cooking Fuel Results by Life Cycle Stage –** Presents LCIA results by fuel type and life cycle stage for all countries.
- **Appendix B: Comparison of Results Updates between Phase I and Phase II Study for India and China –** Presents a comparison of findings between the Phase I and Phase II study.
- **Appendix C**: **Data Quality –** Reports on the quality of data utilized in the Phase II study.

1. GOAL AND SCOPE DEFINITION

1.1 Introduction

Cookstove use in developing countries affects millions of lives on a daily basis with far-reaching consequences. Reducing pollution from cookstoves is a key priority as emissions from cookstoves and open fires with solid fuels are a major health concern and contribute to numerous environmental impacts. The United States Environmental Protection Agency (U.S. EPA) is conducting research to provide data and tools that inform decisions regarding clean cookstoves and fuels for developing countries. Toward this end, EPA previously completed a life cycle assessment (LCA) comparing the environmental footprint of current and potential fuels and fuel mixes used for cooking within India and China (Cashman et al. 2016). This report builds on the original India and China cookstove LCA (referred to throughout this report as the "Phase I study"), by expanding the LCA methodology to include new cooking mix and electrical grid scenarios, additional sensitivity analyses, uncertainty analyses, and a normalized presentation of results. This phase of work also expands the geographic scope of the study to include both Kenya and Ghana.

1.2 Phase II Goal

The goals of Phase II are to expand the geographic scope of the Phase I study, to facilitate the comparison of the current fuel mix with potential future changes to the fuel mix, and to examine the potential environmental effects of stove technology and efficiency upgrades from a life cycle perspective. The study is conducted in accordance with International Standards Organization (ISO 14040 and 14044, the international standards for conducting LCA studies (ISO 2010a, 2010b). Additional goals of the Phase II study are to:

1. Determine the life cycle environmental burdens associated with commonly used cooking fuels in Kenya and Ghana (GACC 2017a);
2. Expand the analysis of cooking fuel impacts in India and China to include updates based on the stove technology mix, building on our earlier study;
3. Perform sensitivity analyses on allocation methodology, calculation of greenhouse gas (GHG) impacts from non-renewable forestry practices, and stove efficiency;
4. Assess new cooking fuel and electrical grid mix scenarios for consideration of future shifts; and
5. Perform uncertainty analyses and calculate normalized results.

This study provides comparative data to inform policy decisions based on an LCA of changes in cooking fuels and stoves on the local and global scale. Environmental issues surrounding cooking fuels are identified, along with opportunities to address these issues based on the choice of cooking fuel and stove technology. By providing results according to life cycle stage, the study gives more specific insight regarding interventions capable of reducing energy use, water consumption, or impacts associated with environmental emissions (e.g., emissions released to air, water, and land). While the study does assess a wide array of environmental indicators, it is not intended to be referenced in isolation, and readers will benefit from considering this study in concert with other research, especially regarding social and economic impacts and potential strategies for implementing sustainable cookstove projects.

Audiences that benefit from information developed through this research include local and national governments in China, India, Kenya, and Ghana, donors and investors (e.g., strategic planners), and researchers (e.g., sustainability scientists).

1.3 Scope of the Study

This section discusses the scope of the study required to accomplish the goals presented above. The LCA components covered include the functional unit, fuel systems, study boundaries, scenario development, impact assessment methods and data quality requirements.

1.3.1 Functional Unit

Results are expressed in terms of a common functional unit, which is defined in relation to the shared functionality of the products under study. This common unit allows fair comparisons to be made between the studied options. As this analysis is a comparison of different fuels used to provide energy for cooking, a functional unit of ***1 gigajoule (GJ) of useful energy delivered to the pot for cooking*** is used as the basis of comparison. Useful energy refers to energy that goes into work and is not lost (e.g., through transmission, distribution, or heat losses at the cookstove).

1.3.2 Geographic and Temporal Scope

Current and projected future cooking fuel and stove technology use within India, China, Kenya, and Ghana constitutes the geographic and temporal scope of this analysis. India and China, covered in the Phase I study, were initially selected because they are both Global Alliance for Clean Cookstoves (referred to throughout this report as “the Alliance”) focus countries. Kenya and Ghana were added in this phase of work to expand the study scope to include African countries. Kenya and Ghana are also Alliance focus countries. Focus countries are those for which the Alliance mobilized resources to grow the global market for clean cookstoves between 2012 and 2014. The Alliance selected focus countries as top priorities for clean cookstoves based on the size of the impacted population, the maturity of the market in each country, the magnitude of need, and the strength of the partner.

While the selection of the geographic scope for this project aligns with regions of focus established by the Alliance, this project does not explicitly define or categorize stoves as clean cookstoves, and instead concentrates specifically on providing quantitative, comparative LCA results that can be used by interested stakeholders to achieve diverse aims in the cooking sector.

In both India and China, approximately half of each country’s population currently uses traditional cooking fuels, and over a million annual premature deaths are attributed to hazardous air pollutants (HAPs) released from combustion of these fuels. Consumption of traditional cooking fuels, in combination with rapid rates of urbanization and industrialization, has contributed to the countries’ resource depletion, deforestation, desertification, and biodiversity loss. According to the United Nations Convention to Combat Desertification, nearly 40 percent of the Asian continent is arid, semi-arid, and dry sub-humid land, with 27 percent of China's land being desertified. Deserts are expanding in both China and India (UNCCD 2015).

Kenya, located in eastern Africa, is the seventh largest country by population in Africa (World Bank 2014b). Over 80 percent of the population in Kenya rely on some form of solid biomass as their cooking fuel. Firewood use is particularly dominant in rural and peri-urban areas and among those with low incomes (GVEP International 2012a, SID 2015), while charcoal and kerosene are more commonly used in Kenyan urban areas. Ghana is Africa's 14th most populous country, with the population evenly divided between urban and rural areas (World Bank 2014b, ADP 2012). Over 40 percent of Ghana's population relies on unprocessed firewood, with over 30 percent using charcoal (GLSS6 2014). In Ghana, there are over 21 million people affected by HAP emissions from cookstoves, with over 13 thousand deaths attributed to these emissions per year (GACC 2017b). Similarly, in Kenya, there are over 36 million people affected by HAP emissions from cookstoves, with over 15 thousand deaths attributed to these emissions per year (GACC 2017c). Overuse of wood-based fuels in both Ghana and Kenya have also accelerated deforestation in these countries (Energy Commission 2010, Dalberg 2013a).

1.3.3 Transparency

The methods, standards, tools, and data used in this study are clearly documented in the report body, appendices, and supplementary information (SI). Detailed supplementary files, documenting the development of custom life cycle inventory (LCI) information for Phase II, are provided as an accompaniment to the main report. Table 1-1 lists the associated SI files, abbreviated in-text references, and a short description of the information contained in each.

Accompanying results files document the LCA model output by impact category for each study scenario. The dynamic results templates allow stakeholders to explore the full breadth of results that were calculated for Phase II, including customizing input parameters to assess impacts on results for the following:

- Cooking fuel mixes,
- Stove technology use,
- Stove thermal efficiency,
- Electricity grid, and
- Forest renewability factor.

Using the supplementary files in combination with this study report will allow interested parties to explore and recreate the LCA results.

Table 1-1. Abbreviated In-text References and Descriptions of Supplementary Information

File Name	In Text Reference	File Description
EPA Phase II Cookstove LCA Results – IN EPA Phase II Cookstove LCA Results – CN EPA Phase II Cookstove LCA Results - KE EPA Phase II Cookstove LCA Results - GH	Result Files	One result file is available for each study country (IN = India, CN = China, KE = Kenya, GH = Ghana). The files are dynamic and allow the user to explore various results presentations, allowing specification of custom fuel mixes and parameters considered within the sensitivity analysis. Raw LCA results as exported from openLCA are included in these files.
SI1. Stove Use and Emissions Supplementary Information	SI1	Documents stove emissions information, stove thermal efficiency values, and estimates of stove technology use for each country studied.
SI2. Stove LCI Supplementary Information	SI2	Documents specific stove records and associated emissions values for each stove grouping, as described in Section 2.2. Documentation of standard deviation used in the Monte Carlo analysis for each pollutant is also available in the file.
SI3. Fuel Mix Scenario Supplementary Information	SI3	Documents primary literature sources and calculations used to estimate current and potential future fuel mix scenarios for each study country.
SI4. Cookstove Electricity Scenario Supplementary Information	SI4	Documents primary literature sources and calculations used to specify current and potential future electricity grid mix scenarios for each country studied.
SI5. Crop Residue Supplementary Information	SI5	Documents primary literature sources and calculations used to develop crop production LCI information and allocation factors used in the sensitivity analysis.
SI6. Charcoal Kiln Supplementary Information	SI6	Documents primary literature sources and calculations used to develop the average and improved performance charcoal kiln unit processes for Kenya and Ghana.
SI7. Biogas Modeling Supplementary Information	SI7	Documents primary literature sources and calculations used to develop the bioslurry land application LCI and biogas allocation factors.

1.3.4 Cooking Fuel Systems

This LCA considers the main cooking fuels currently used in India, China, Kenya, and Ghana, as well as several emerging cooking fuel options such as sugarcane ethanol, biomass pellets, and electricity. Table 1-2 provides a list of the cooking fuels considered in this study, accompanied by a brief description of each fuel. This table also lists the countries for which each fuel is considered.

Table 1-3 lists the current cooking fuel mix in each of the four countries. This study also considers possible cooking fuel mix shifts for the countries covered, as discussed in Section 3. Detailed profiles of individual fuels, fuel heating values, and stove thermal efficiencies by cooking fuel type are presented in Section 2.1 and Section 2.2.1, while the fuel mix scenarios are described in Section 3.1.

Throughout this report, and the literature in general, the terms traditional, improved, and modern are used as categorical descriptions for both cookstoves and cooking fuels. The International Energy Agency (IEA) uses the terms traditional, intermediate, and modern to describe fuel groupings. IEA notes that the use of these terms is not meant to imply a ranking and refers instead to how well established a fuel is within a given nation (IEA 2006). This report does not utilize the term intermediate and instead refers to all fuels as either traditional or modern, with traditional fuels having a longer history of use. In this study, coal, charcoal, firewood, crop residues, dung, and kerosene are all considered to be traditional fuels. Liquefied petroleum gas (LPG), natural gas, coal gas, sugarcane ethanol, biogas, and electricity are referred to as modern fuels.

The terms traditional and modern, as well as the additional term improved, can also refer to stove technologies. This usage follows directly from the use of these terms in reference to the fuels themselves. As noted, traditional fuels have a longer history of use, and over time the original cookstove technologies used to combust these fuels have seen enhancements to increase thermal efficiency, cooking quality, and to decrease a user's exposure to irritating or harmful emissions. Stoves burning traditional fuels that incorporate features designed to accomplish these goals are referred to as improved. Examples of such features include insulated combustion chambers, chimney flues, and pot skirts. All stoves that burn modern fuels are considered to be modern.

While the terminology used in this study is generally associated with improved performance along the progression from traditional to improved fuels and cookstoves, this terminology does not imply a strict quantitative improvement in any single metric of stove performance. Detailed results of this and other studies should be consulted prior to making statements or assumptions regarding the relative environmental performance of individual fuels and cookstoves.

Table 1-2. Cooking Fuel List and Description

Fuel Type	Fuel	Description	Countries
Traditional	Coal	A solid fossil fuel used widely for heating and cooking, especially in China (GACC 2015). Coal powder is the most popular form of coal used today.	India
			China
	Dung	Dried animal waste, usually from cows, is used as an inexpensive fuel in rural areas.	India
			India

Table 1-2. Cooking Fuel List and Description

Fuel Type	Fuel	Description	Countries
Traditional	Crop Residue	Unprocessed biomass harvested as a by-product of food production in agricultural regions. Crop residues can include straws, stems, stalks, leaves, husks, shells, peels, etc.	China Ghana
	Firewood	An unprocessed, solid wood fuel that is one of the largest energy sources in all four study nations. Much of the firewood used is manually gathered from local forests.	India China Kenya Ghana
	Charcoal	A product made of carbonized firewood. Carbonization is the process of burning firewood in a low oxygen environment such as a traditional earthen mound kiln to increase the fuel energy density and decrease transport weight.	India Kenya Ghana
	Kerosene	Also referred to as paraffin, a liquid fossil fuel product often derived from crude oil and used for heating, lighting, and cooking.	India China Kenya Ghana
Modern	LPG	A gas, which is a co-product of the production of natural gas and/or crude oil (GACC 2015). LPG is most widely used by urban residents and is experiencing expanded use in all four countries studied.	India China Kenya Ghana
	Natural Gas	A fossil fuel-derived gas that is piped to customers via a centralized distribution pipeline. Natural gas use is limited to urban areas and is not yet a prevalent cooking fuel in the countries studied.	China India
	Coal Gas	A gaseous fuel that is a product of the coal gasification process.	China
	Electricity	Electrical energy in each country is assumed to be produced via the centralized electrical grid according to the national average fuel mix for the year 2013.	India China Kenya Ghana
	Ethanol	A liquid fuel is produced through the distillation of various agricultural products or wood. Sugarcane is the considered feedstock in this study due to its prevalent production in India, Kenya, and China.	India China Kenya Ghana
	Biogas	A methane-rich gas produced through the anaerobic digestion of organic wastes. Biogas can be generated from animal, human and kitchen wastes, as well as some crop residues.	India China Kenya Ghana
	Biomass Pellets	Highly densified biomass material. Assumed to be derived from wood in this study.	India China Kenya Ghana

Table 1-3. Fuels Used for Cooking in Countries Studied

Fuel[5]	Fuel Type	Fuels Used for Cooking			
		India[1,2,3] (%)	China[4,5] (%)	Kenya[6] (%)	Ghana[7] (%)
Coal	Traditional	1.15	28.9	-	-
Dung		10.6	-	-	-
Crop Residue		8.90	12.0	-	0.412
Firewood		49.0	14.7	64.9	45.9
Charcoal		1.15	-	17.0	31.5
Kerosene		3.20	0.300	11.6	0.157
LPG	Modern	25.2	31.1	5.02	21.7
Natural Gas		-	2.40	-	-
Electricity		0.400	10.6	0.803	0.315
Biogas		0.400	-	0.703	-
Total		100	100	100	100

Sources and Notes: [1] Dalberg 2013b, [2] Gov. of India 2014, [3] Venkataraman et al. 2010, [4] NBSC 2008, [5] Dalberg 2014, [6] KNBS 2012, [7] GLSS6 2014
[5] Coal gas, biomass pellets and ethanol are not present in the current cooking fuel mix of any country.

1.3.5 System Boundary

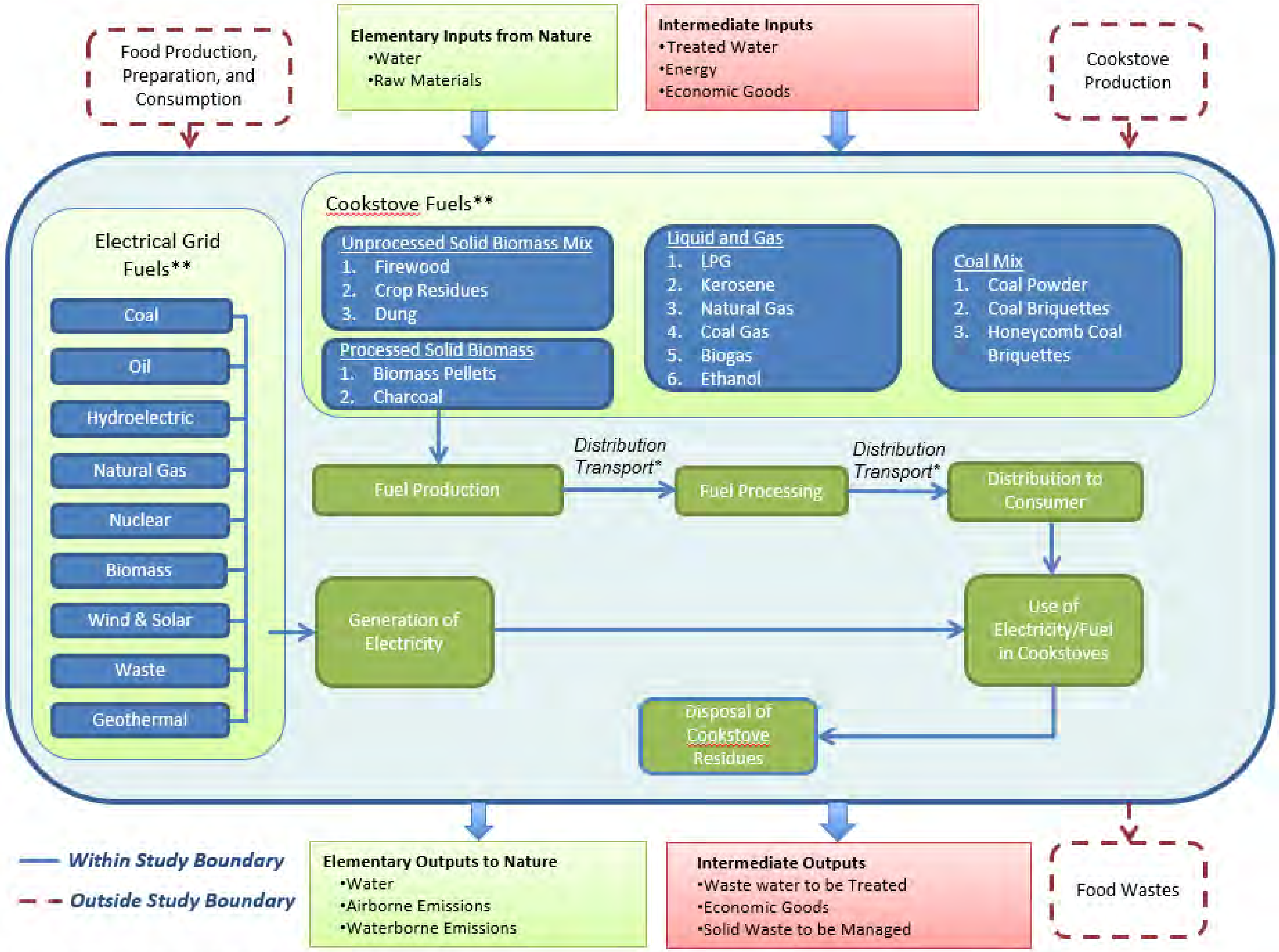
The following life cycle stages are included for each cooking fuel system:

- **Production** of the cooking fuel feedstock, including all stages from extraction or acquisition of the feedstock material from nature through production into a form ready for processing into cooking fuel (e.g., cultivation and harvesting of sugarcane, extracting crude oil from wells).
- **Processing** of the fuel into a form ready to be used in a cookstove.
- **Distribution** of fuels from the processing location to a retail location or directly to the consumer. Distribution also includes bottling for fuels stored in cylinders (e.g., LPG).
- **Use** of the fuel via combustion of the fuel or use of electricity in a cookstove, including disposal of any combustion wastes or residues (e.g., ash).

Figure 1-1 provides the general study system boundaries for all countries covered. Fuel production and processing consists of all necessary steps, beginning at resource extraction, which are required to make the fuel ready for use in a cookstove. For ethanol, this includes impacts for growth and harvesting of the sugarcane. For crop residues in the baseline results, burdens begin at collection of the biomass from the field, with all cultivation burdens assigned to the primary food crop. The effects of allocating a share of crop production impacts to crop residue are examined as part of the sensitivity analysis. Impacts of firewood harvesting are not included in the study, however carbon dioxide (CO_2) emissions do contribute to global climate change potential (GCCP) for the fraction of forest products produced using non-renewable practices. In the case of electricity, power generation, as well as transmission and distribution losses, are included within the system boundaries. Additionally, this study accounts for transportation requirements between all life cycle stages within the boundaries of this study. Specific processing steps included in the analysis are described in greater detail for individual fuels in Section 2.1.

Cookstove production and distribution, human energy expended during collection of fuels, and the production, preparation, consumption, and disposal of food and food wastes are outside the boundaries of this project. The rationale for excluding these stages is discussed in the next section (Section 1.3.5.1).

The use phase includes the combustion of the cooking fuels and associated stove emissions. The types and quantities of air emissions associated with fuel use depend on the fuel's elemental composition (e.g., average fixed carbon, ash content, and volatile matter) and the cookstove technology or technology mix (e.g., thermal efficiency) for each country, which affects the quantity of fuel that must be consumed to deliver 1 GJ of cooking energy. At fuel end-of-life (EOL), solid residues from the combustion of cookstove fuels (bottom ash and carbon char) are disposed. The major components of these wastes are determined by the type of fuel combusted. For example, biomass fuel combustion typically results in ash containing silica, alumina, calcium oxides, sodium, magnesium, and potassium. These wastes are assumed to be disposed of by land application, whereby the wastes in question are spread out over a landscape, often as an agricultural amendment, to be assimilated by the environment.



*Human energy expenditures are not included.

** Not all fuels are utilized in every study nation, please refer to Sections 1.3.4 for current fuel and electricity use and Sections 3.1 and 3.2 for potential future cooking fuel and electricity grid fuel use in each country.

Figure 1-1. Study system boundaries of the baseline scenario for covered countries.

1.3.5.1 System Components Excluded

The following components of each system are not included in this study.

Cookstove Production and Distribution. All burdens associated with production and distribution of the cookstoves themselves are excluded from the analysis, as the focus of the study is production and use of cooking fuels. A previous LCA examining production of fuel-efficient cookstoves found that the use phase significantly dominates life cycle GHG emissions regardless of cooking fuel type (Wilson 2016). Life cycle impacts of the stove relative to fuel production and use are assumed to be negligible.

Human Energy Expended During the Collection or Use of Fuels. This analysis does not include human biological energy or emissions. Shifts in the mix of fuels may decrease the overall human energy and emissions expended during the distribution phase in some cases (e.g., shifting to fuels with higher energy density that are easier to transport or that do not require consumer transport such as electricity). While outside the scope of this study, there are important benefits to reducing the time and effort associated with the collection of solid biofuels, particularly as they relate to women's health and safety. The benefits and burdens of such changes would be better captured by qualitative or analytical methods apart from LCA.

Food and Food Wastes. The focus of this study is the provision of cooking energy and is intended to be independent of the food itself. All burdens associated with production, preparation, storage, consumption, and disposal of the food being prepared are excluded from the analysis.

Capital Equipment and Infrastructure. Energy and wastes associated with the manufacture of capital equipment and infrastructure are excluded from this analysis, including equipment to manufacture buildings, motor vehicles, and industrial machinery, as well as roads and electricity distribution infrastructure used to distribute fuels throughout the supply chain and to end users. In general, these types of capital equipment and infrastructure are used to produce and deliver large quantities of product output over a useful life of many years. Thus, energy and emissions associated with the production of these facilities and equipment generally become negligible when allocated over the total amount of output or service over their useful lives (Berglund 2006).

Stove Stacking. The transition from one cooking system to another does not always occur instantaneously. In communities that are undergoing transitions to a new cooking fuel type, field observations indicate that very often individual homes will initially use a mixture of new and traditional cooking systems. This phenomenon, known as 'stove-stacking,' allows households to take advantage of the differences that exist between the stove and cooking fuel combinations that they employ. While this would ultimately affect the pace of change and the attendant shift in environmental impacts, it represents a dynamic force operating at a household level (Hiemstra-van der Horst and Hovorka 2008) that lies outside the study scope. This study focuses on scenarios encompassing the national cooking fuel mix, which could include households using a mixture of fuels, although this was not explicitly considered when developing the cooking fuel scenarios.

Effect of Stove Operational Practice. Practical and environmental performance of a cookstove is determined not only by the selection of fuel and stove technology, but also based on stove operational conditions. The result of many cookstove emissions tests are associated with operation of a cooking stove under ideal or laboratory conditions. A small number of studies look at field conditions. The availability of field study results is not extensive enough to provide a comprehensive source of data if considered on its own. Given this, the results of both field and laboratory studies have been combined when compiling LCI information for each stove grouping, and thereby contribute to the variation represented in the uncertainty results. As such, it beyond the scope of this project to quantify the effect of variation in operational practice on environmental performance, which should be considered when interpreting results.

Human Exposure to Emissions. This study does not include the detailed analysis of human exposure to cookstove emissions that would be required to accurately estimate the human health impacts of household cooking. For example, if cookstoves burning solid fuels are more commonly used outdoors than liquid/gas alternatives, then there may not be a one-to-one relationship between cookstove emissions and human exposure between these alternatives. Similarly, upstream emissions at the point of manufacture can be expected to have a lower exposure factor than emissions from the cookstove themselves, thereby affecting the potential for human health impact. Such differences that affect human exposure to cooking emissions are outside of the scope of this study, and must be considered separately.

1.3.6 Data Sources Summary

The majority of stove emission data was extracted from existing studies in publicly available academic literature. Much of this research has been supported by US EPA Office of Research and Development's small-scale combustion evaluation program in collaboration with the Global Alliance, the World Bank, and other research efforts to support reducing health and environmental pollution associated with cookstove use. The SI contains detailed LCI data for the life cycle stages modeled for each cooking fuel system. Baseline LCI data for China and India from the Phase I study can be found in Appendix A of that document (Cashman et al. 2016). Data were assembled according to the procedures established in the project Quality Assurance Project Plan (QAPP) *"Quality Assurance Project Plan for Comparative Life Cycle Assessment of Cooking Fuel Options in China and India"*, approved August 25, 2014. Data quality and data requirements are covered in more detail in Section 1.4.

1.3.7 Life Cycle Impact Assessment Methodology and Impact Categories

Life Cycle Impact Assessment (LCIA) helps with interpretation by consolidating a lengthy LCI into a smaller number of relevant indicators. LCIA is defined in ISO 14044 Section 3.4 as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO 2010b)." In the LCIA phase, the inventory of emissions is first classified into categories in which the emissions may contribute to impacts on human health or the environment. Within each impact category, the emissions are then normalized to a common reporting basis, using characterization factors that express the impact of each substance relative to a reference substance.

Characterization factors are defined to quantify the impact potential of LCI results. There are two main methods to develop LCIA characterization factors. The 'midpoint' method links LCI results to categories of commonly defined environmental concerns like eutrophication potential and global climate change potential. The 'endpoint' method further models the causality chain of environmental stressors to link LCI results to environmental damages (e.g., final impacts to human and ecosystem health). ISO standards allow the use of either method in the LCIA characterization step. Overall, indicators closer to the inventory result (midpoint indicators) have a higher level of scientific consensus, as less of the environmental mechanism is modeled. Conversely, endpoint and damage-oriented characterization models inevitably include more aggregation, or more assumptions (e.g., about fate and transport, exposures/ingestion, etc.). To reduce uncertainty in communication of results, this LCA focuses on indicators at the midpoint level.

1.3.7.1 Scope of Impact Assessment

This study addresses global, regional, and local impact categories of relevance to the cookstove sector such as air emissions leading to human health issues, energy demand driving depletion of bio-based and fossil-fuel resources, and GHG and black carbon (BC) and short-lived climate pollutant emissions causing both short-term and long-term climate effects. For most of the impact categories examined, the ReCiPe impact assessment method is utilized to represent global conditions (Goedkoop et al. 2008). Characterization factors, which are developed based on established impact pathways, form the basis of impact assessment methods such as ReCiPe. An impact pathway is a series of quantifiable relationships that can be used to link LCI emissions to units of environmental impact (e.g. kg CO_2-eq for GCCP). Characterization factors in ReCiPe were originally developed for global or European conditions and are not specific to any of the study countries. The characterization factors used in this study are associated with ReCiPe's hierarchist cultural perspective, which makes characterization assumptions based on what ReCiPe's authors consider to be standard policy perspectives and time horizons (i.e., consensus model) for the included impact categories (Goedkoop et al. 2008). Currently, no established LCIA method exists specifically for the scope of India, China, Kenya, or Ghana.

For the category of GCCP, a global impact, contributing elementary flows are characterized using factors reported by the Intergovernmental Panel on Climate Change (IPCC) in 2013 with a 100-year time horizon (IPCC 2013). Considerations for biogenic carbon accounting are covered in Section 4.1 and Section 4.2. BC and co-emitted species are characterized to BC – equivalents (eq) based on a novel method released by the Gold Standard Foundation (GSF) (GSF 2015). A detailed discussion of the BC methodology is presented in Section 4.3. Cumulative energy demand (CED) and water depletion are also included as inventory indicators. Energy and water inventory indicators are not associated directly with environmental impacts but rather provide a cumulative count of energy and water resources used within the study system. CED includes both renewable and non-renewable energy sources.

A summary of the LCI and LCIA categories and methods used in this study is presented in Table 1-4. While this study focuses on environmental impacts and does not include impact categories that focus exclusively on human health, several included impact categories are closely associated with both environmental and human health impacts. These emission types include emissions leading to BC, particulate matter formation potential (PMFP), and photochemical oxidant formation potential (POFP), all of which can lead to eye irritation, respiratory disease, increased risk of infection, and cancer. Linking these emissions definitively to human health impacts would introduce a higher level of uncertainty to the study results. Human health impacts are dependent not only on emission quantities but also on the fate and transport of the emitted substances and the concentrations and pathways by which organisms are exposed to these substances. These detailed types of exposure information are not tracked in an LCI, requiring additional assumptions about the environmental mechanism to be made by the developer of the LCIA methodology. While human health impacts are not explicitly estimated by this study, pertinent impact categories related to known human health impacts of cookstove use are included in the analysis.

Table 1-4. Environmental Impact Category Descriptions and Units

Impact/Inventory Category	Description	Unit
Global Climate Change Potential	The GCCP impact category represents the heat trapping capacity of GHGs over a 100-year time horizon. All GHGs are characterized as kg CO_2 equivalents according to the IPCC 2013 5th Assessment Report global warming potentials.	kg CO_2 eq
Cumulative Energy Demand	The CED indicator accounts for the total usage of non-renewable fuels (natural gas, petroleum, coal, and nuclear) and renewable fuels (such as biomass and hydro). Energy is tracked based on the heating value of the fuel utilized from point of extraction, with all energy values summed together and reported on a megajoule (MJ) basis.	MJ
Water Depletion Potential (WDP)	WDP results, in alignment with the ReCiPe impact assessment method, are based on the volume of fresh water inputs to the life cycle of the assessed fuels. Water may be used in the 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 that the water is returned at a degraded quality, which constitutes a consumptive use. Water consumption includes evaporative losses from establishment of hydroelectric dams.	m^3
Black Carbon and Short-Lived Climate Pollutants	BC, formed by incomplete combustion of fossil and bio-based fuels, is the carbon component of particulate matter ($PM_{2.5}$) that most strongly absorbs light and thus has potential short-term (e.g., 20-year) radiative forcing effects (e.g., potential to contribute to climate warming). Organic carbon (OC) is also a carbon component of PM and possesses light-scattering properties typically resulting in climate cooling effects. PM from the cookstove sector is typically released with criteria pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur oxides (SO_x), which may result in additional warming impacts or exert a cooling effect on climate. This indicator characterizes all PM and co-emitted pollutants to BC equivalents depending on the relative magnitude of short-term warming or cooling impacts. The BC method is based on the novel GSF method (GSF 2015).	kg BC eq
Particulate Matter Formation Potential	PMFP results in health impacts such as effects on breathing and respiratory systems, damage to lung tissue, cancer, and premature death. Primary pollutants (including $PM_{2.5}$) and secondary pollutants	kg PM_{10} eq

Table 1-4. Environmental Impact Category Descriptions and Units

Impact/Inventory Category	Description	Unit
	(e.g., SO_x and NO_x) leading to PM formation are characterized here as kg PM_{10} eq based on the ReCiPe impact assessment method.	
Terrestrial Acidification Potential (TAP)	TAP quantifies the acidifying effect of substances on their environment. Important emissions leading to terrestrial acidification include sulfur dioxide (SO_2), NOx, and ammonia (NH_3). Results are characterized as kg SO_2 eq according to the ReCiPe impact assessment method.	kg SO_2 eq
Freshwater Eutrophication Potential (FEP)	Freshwater eutrophication assesses the potential impacts from excessive loading of macro-nutrients to the environment and eventual deposition in freshwater. Pollutants covered in this category are all phosphorus (P)-based (e.g., phosphate, phosphoric acid, elemental P), with results characterized as kg P eq based on the ReCiPe impact assessment method.	kg P eq
Photochemical Oxidant Formation Potential	The POFP (e.g., smog formation) results determine the formation of reactive substances that cause harm to human health and vegetation. Results are characterized here to kg of non-methane volatile organic compounds (NMVOCs) eq according to the ReCiPe impact assessment method. Some key emissions leading to POFP include CO, methane (CH_4), NOx, NMVOCs, and SOx.	kg NMVOC eq
Ozone Depletion Potential (ODP)	Measures stratospheric ozone depletion. Important contributing emissions include chlorofluorocarbon (CFC) compounds and halons. It is likely that ozone depletion is of lower importance for cookstoves fuels compared to other impact categories. There will be differences between stove options as fossil fuels generate ozone depleting emissions within their supply chain that are absent in the biomass options. However, the ODP category has become less critical following the regulation of the worst offending ozone-depleting chemicals.	kg CFC-11 eq
Fossil Depletion Potential (FDP)	Fossil fuel 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 and according to the ReCiPe impact assessment method.	kg oil eq

1.4 Quality Assurance

In accordance with the project's Quality Assurance Project Plan (QAPP) entitled *Quality Assurance Project Plan for Comparative Life Cycle Assessment of Cooking Fuel Options in China and India* approved by EPA on August 25, 2014, ERG collected or adapted existing data to develop: (1) cooking fuel production LCIs, (2) cookstove use LCIs, (3) national cooking fuel mix scenarios, (4) stove technology use estimates, (5) electrical grid mix scenarios, and (6) forest renewability factors that encompass the main data requirements for this study (ERG 2014). The collected data sources include peer-reviewed literature, government and NGO reports, and national survey information. ERG evaluated the collected information for completeness, accuracy, and reasonableness. In addition, ERG considered publication date and accuracy/reliability when reviewing data quality. Finally, ERG performed conceptual, developmental, and final product internal technical reviews of the openLCA model and supplementary files used to document the compilation and development of information listed above. The remainder of this section first outlines the study data quality evaluation, followed by a discussion of quality assurance procedures implemented.

1.4.1 Data Quality Evaluation

ISO standards 14040 and 14044 detail various aspects of data quality and data quality analysis. These ISO Standards state: "descriptions of data quality are important to understand the reliability of the study results and properly interpret the outcome of the study (ISO 2010a, 2010b)." These ISO Standards list three critical data quality criteria: time-related coverage, geographical coverage, and technology coverage. The following subsections discuss these three critical data quality criteria and the typical specifications associated with high quality data. Additional data quality criteria evaluated include data source reliability and completeness.

The geographic scope of the study encompasses cooking fuel use in India, China, Kenya, and Ghana. However, some cooking fuels or upstream inputs to fuel production/processing are imported from other regions of the world. High quality data and information for geography-dependent processes (e.g., energy production) were obtained from country-specific articles and databases. Data for technology-based processes are based on the most recent average country-specific technology mix (e.g., the current production methods China employs for mining and processing coal). It is more difficult to evaluate data quality for future technologies not yet in use or that currently have a small market share. When more specific information was not available, data quality for future technological processes was based on current technological processes used in the same country. For example, for a scenario with increased use of natural gas to produce electricity in China, the future natural gas production is modeled assuming China will produce natural gas in the future using the same methods it currently employs.

'High quality temporal data' typically refers to data that are less than six years from the reference period. The wide scope of this project and the nature of national data for these four countries has necessitated the establishment of a reference period, rather than a single reference year. The reference period for country-specific information such as cooking fuel mix, stove technology use, and electrical grid mix is believed to be most representative of the period between 2008-2013. The use of data representative of a date prior to the reference period has been required where more recent information is unavailable. Projected scenarios such as the future electrical and cooking fuel mix scenarios, are generally associated with a 20- to 30-year time horizon. This period should be used only for general guidance in interpretation. In cases where the supporting literature provides a specific time period estimate, that estimate has been provided. Standardization of temporal scope has been sought to ensure that differences in study results are focused on material and process differences for the fuels (and associated stove efficiencies) rather than as a result of disparities in data quality available between nations.

Table 1-5 presents the data quality criteria ERG used when evaluating the data collected. Not all data quality criteria are applicable for every data source referenced in this project. Actual data quality scores are documented in Appendix C. Data fields for which a data quality criterion is not relevant are clearly noted, and the specific SI file used to document the data requirement is listed to facilitate review of the underlying references and calculations. ERG documented qualitative descriptions of source reliability, completeness, temporal correlation, geographical correlation, and technological correlation. Additional notes on how data quality criterion were applied to the data types utilized in this project are included in Appendix C-1.

Table 1-5. Data Quality Rubric

Quality Metric	Data Quality Criteria	Quality Estimate
Data Source Reliability	Data verified based on measurements.	**High**
	Data verified based on some assumptions and/or standard science and engineering calculations.	**Medium High**
	Data verified with many assumptions, or non-verified but from quality source.	**Medium**
	Qualified estimate.	**Medium Low**
	Non-qualified estimate.	**Low**
Data Completeness	Representative data from a sufficient sample of sites over an adequate period, with records for all necessary inputs/outputs.	**High**
	Smaller number of sites, but an adequate period.	**Medium High**
	Sufficient number of sites, but a less adequate period.	**Medium**
	Smaller number of sites and shorter periods or incomplete data from an adequate number of sites or periods.	**Medium Low**
	Representativeness unknown or incomplete data sets.	**Low**
Temporal Data Quality	Less than 3 years of difference to year of study/current year.	**High**
	Less than 6 years of difference.	**Medium High**
	Less than 10 years of difference.	**Medium**
	Less than 15 years of difference.	**Medium Low**
	Age of data unknown or more than 15 years of difference.	**Low**
Geographical Data Quality	Data from area under study.	**High**
	Average data from larger area or specific data from a close area.	**Medium High**
	Data from area with similar production conditions.	**Medium**
	Data from area with slightly similar production conditions.	**Medium Low**
	Data from unknown area or area with very different production conditions.	**Low**
Technological Data Quality	Data from technology, process, or materials being studied.	**High**
	Data from a different technology using the same process and/or materials.	**Medium High**
	Data on related process or material using the same technology.	**Medium**
	Data or related process or material using a different technology.	**Medium Low**
	Data or poorly related process or material using a different technology.	**Low**

1.4.2 Internal QA Review Procedures

ERG developed SI files containing all the necessary information and data required to execute the compilation of LCI information and the establishment of sensitivity scenarios. All SI files were reviewed by a team member knowledgeable of the project, but who did not develop the input files. The reviewer ensured the accuracy of the data transcribed into the input files, the technical soundness of methods and approaches used and the accuracy of the calculations.

ERG input all LCI data developed into the openLCA software (GreenDelta 2016). A team member knowledgeable of the project, but who did not develop the model, reviewed the openLCA model to ensure the accuracy of the data transcribed into the software. The openLCA model was also reviewed to ensure that each elementary flow (e.g., environmental emissions, consumption of natural resources, and energy demand) was characterized under each impact category for which a characterization factor was available. The draft final fuel system models were reviewed prior to calculating results to make certain all connections to upstream processes and weight factors were valid. LCIA results were then calculated by generating a contribution analysis for the selected cookstove product system based on the defined functional unit of 1 GJ of heat delivered for cooking. Similarly, after the LCIA results were generated and exported from openLCA to results spreadsheets, the generated spreadsheet results were reviewed by a team member who did not calculate the results. The ERG reviewer compared the spreadsheet LCIA results against generated results in the final openLCA model. All Phase II results were also compared to similar results from Phase I (if applicable) to ensure any changes were reasonable and accounted for. Differences between Phase 1 and Phase II LCIA results are documented in Appendix B of this report.

2. COOKING FUEL AND STOVE DESCRIPTIONS AND METHODOLOGY

This section describes the method for constructing the relevant cooking fuel LCIs and identifies stove technologies used in the LCA model. The term LCI refers to the inventory of relevant energy and material inputs and environmental releases associated with a cooking fuel across all life cycle stages assessed.

2.1 Fuel System Model Descriptions

For India, cookstove fuel system modeling assumptions are based largely on work conducted by Singh and colleagues (2014a/b) for all cookstove fuels except sugarcane ethanol and biomass pellets. Sugarcane ethanol production in India is derived from a study by Tsiropoulos and colleagues (2014), with fuel combustion emission values coming from laboratory tests carried out at the Aprovecho Research Center (Berick 2006, MacCarty 2009). For the Chinese cooking fuels, fuel modeling data are primarily from work by Zhang and colleagues (2000). For both China and India, biomass pellet production is from work by Jungbluth and colleagues (2007), while combustion of the pellets is modeled based on emission and stove efficiency profiles from Jetter et al. (2012). Cooking fuel data for Kenya and Ghana are largely drawn from the work of Afrane and Ntiamoah (2011).

Stove emission profiles drawn from the literature, which are used to develop use phase LCI data for each stove-fuel combination, are summarized in Table 2-1. In addition to listing the sources used, this table specifies the number of emission records that were aggregated to derive a specific stove LCI unit process. Not all emission records provide a quantity for each pollutant of interest in this study, please see SI2 for a more detailed presentation of the sources utilized for each stove group and the pollutants covered by each. Each of these unit processes is defined by the fuel type, stove type, and country or region. When possible, emission profiles that were specific to a study country were used. For cases in which an emission profile was not available for a specific cooking fuel and country combination, all stove emission profiles available were aggregated into LCI unit processes to represent a global average. This global average was then used as a proxy dataset for the country and fuel combinations lacking specific regional emission profiles. These global average emissions profiles were, however, linked to upstream fuel extraction, production and processing LCI specific to the country of interest.

Documentation of the processed cookstove fuel heating values is provided in the next section, followed by a discussion on the supply chain for each fuel. Upstream processes such as transport and ancillary material inputs are modeled using information from the National Renewable Energy Laboratory's (NREL's) US Life Cycle Inventory (US LCI) Database and Ecoinvent v2.2. The US LCI is a publicly available LCI source specific to US conditions (NREL 2012) and Ecoinvent v2.2 is a private Swiss LCI database with data for many global unit processes (Ecoinvent Centre 2010). Where possible, these upstream databases are adapted to the geographic scope of interest, i.e., by linking process electricity requirements to the country-specific electricity grid mix.

Table 2-1. Emission Profile Sources for Each Stove Type by Study Country

Fuel	Stove Type	Country	Stove Emission Records	Sources
Coal	Traditional	India	1	1
Coal, Powder	Traditional	China	6	3,12
	Improved	China	3	3,12
Coal, Briquette	Improved	China	4	3,12
Coal, Honeycomb	Traditional	China	8	3,12,15,16
	Improved	China	13	3,12,17
Dung	Traditional	India	11	1,2,3,6
	Improved	India	4	3,6
Crop Residue	Traditional	India	14	1,2,3,6
		China	12	3,11,15
		Global	26	1,2,3,6,11,15
	Improved	India	8	3,6
		China	26	3,12,13,14,18,19
Firewood	Three-stone	India	4	3,6
		Global	4	7,8
	Traditional	India	14	1,2,3,6
		China	21	4,3,10,11
		Global	16	4,5
	Improved	India	16	3,4,5,6
		China	35	3,12,13,14
		Global	28	4,7
Charcoal	Traditional	Global	5	4,8,9
	Improved	India	2	1,3
	Improved	Kenya	4	7
	Improved	Ghana	2	7
Kerosene	Improved, Pressure	India	2	3,6
	Improved, Wick	India	2	3,6
	Improved	China	4	3,12
		Global	8	3,6,12
LPG	Modern	India	2	3,6
		China	4	3,12

Table 2-1. Emission Profile Sources for Each Stove Type by Study Country

Fuel	Stove Type	Country	Stove Emission Records	Sources
		Global	6	1,3,6
Natural Gas	Modern	India, China	3	3,12
Coal Gas	Modern	China	2	3,12
Electric	Modern	All Countries	-	-
Sugarcane Ethanol	Modern	All Countries	4	21
Biogas	Modern	India, China	3	1,6,3
		Kenya, Ghana	1	20
Biomass Pellets	Modern	All Countries	4	7, 22

Sources: [1] Singh et al. 2014a/b, [2] Saud et al. 2012, [3] Zhang et al. 1999, [4] Bhattacharya et al. 2002b, [5] Bhattacharya et al. 2002a, [6] Smith et al. 2000, [7] Jetter et al. 2012, [8] Sweeney 2015, [9] Booker 2012, [10] Shen et al. 2013, [11] Shen et al. 2012b, [12] Zhang et al. 2000, [13] Shen et al. 2012a, [14] Wang et al. 2009, [15] Shen et al. 2010b, [16] Shen et al. 2010a, [17] Zhi et al. 2008, [18] Cao et al. 2008, [19] Wei et al. 2014, [20] Afrane and Ntiamoah 2011, [21] MacCarty 2009, [22] Carter et al. 2014

2.1.1 Processed Fuel Heating Values

Table 2-2, Table 2-3, Table 2-4, and Table 2-5 list the lower and higher heating values (LHV, HHV) for cooking fuels in India, China, Kenya, and Ghana, respectively. Lower heating values in combination with stove thermal efficiency values are used to calculate the quantity of fuel required per GJ of delivered cooking energy. HHVs are used to calculate CED results within the fuel system unit processes. Associated cookstove thermal efficiencies for each country and fuel combination are provided in Table 2-7.

Table 2-2. Heating Values of Cooking Fuels in India

Fuel Type	Lower Heating Value (LHV) MJ/kg	Higher Heating Value (HHV) MJ/kg	Source[1]
Firewood	14.0	15.8	Singh et al. 2014a
Crop Residue	12.8	14.6	Singh et al. 2014a
Dung Cake	11.9	13.3	Singh et al. 2014a
Charcoal Briquettes from Wood	27.4	27.9	Singh et al. 2014a
Biomass Pellets	16.5	17.8	Jetter et al. 2012
Ethanol from Sugarcane	27.0	29.7	GREET 2008, MacCarty 2009
Biogas from Dung	18.2	19.9	Singh et al. 2014a, calculated[2]

Table 2-2. Heating Values of Cooking Fuels in India

Fuel Type	Lower Heating Value (LHV) MJ/kg	Higher Heating Value (HHV) MJ/kg	Source[1]
LPG	45.2	48.9	Singh et al. 2014a, calculated
Natural Gas	51.3	56.8	Zhang et al. 2000, calculated[2]
Kerosene	42.9	49.0	Singh et al. 2014a
Hard Coal	11.8	12.3	Singh et al. 2014a, calculated[2]

[1] Where two sources are listed, first refers to LHV. Second refers to HHV.
[2] HHV is calculated based on ratio of HHV/LHV for similar fuel as documented in SI1. HHVx = LHVx*(HHVy/LHVy)

Table 2-3. Heating Values of Cooking Fuels in China

Fuel Type	Lower Heating Value (LHV) MJ/kg	Higher Heating Value (HHV) MJ/kg	Source[1]
Firewood	15.3	17.3	Zhang et al. 2000, calculated[2]
Crop residue	16.1	18.3	Zhang et al. 2000, calculated[2]
Biomass Pellets	16.5	17.8	Jetter et al. 2012
LPG	49.0	53.0	Zhang et al. 2000, calculated[2]
Kerosene	43.3	49.5	Zhang et al. 2000, calculated[2]
Natural Gas	51.3	56.8	Zhang et al. 2000, calculated[2]
Coal Gas	43.8	48.0	Zhang et al. 2000, calculated[2]
Honeycomb Coal	19.2	20.3	Zhang et al. 2000, calculated[2]
Coal, Powder	27.3	28.8	Zhang et al. 2000, calculated[2]
Coal, Briquette	13.9	14.6	Zhang et al. 2000, calculated[2]
Biogas from Dung	18.2	19.9	Singh et al. 2014a, calculated[2]

[1] Where two sources are listed, first refers to LHV. Second refers to HHV.
[2] HHV is calculated based on ratio of HHV/LHV for similar fuel as documented in SI1. HHVx = LHVx*(HHVy/LHVy)

Table 2-4. Heating Values of Cooking Fuels in Kenya

Cooking Fuel Type	Lower Heating Value (LHV) MJ/kg	Higher Heating Value (HHV) MJ/kg	Source[1]
Firewood	14.0	15.8	Singh et al. 2014a
Charcoal, Average Kiln	29.6	30.4	calculated[2], Pennise et al. 2001
Charcoal, High-Performing Kiln	30.2	31.0	calculated[2], Pennise et al. 2001
Kerosene	42.9	49.0	Singh et al. 2014a
LPG	45.8	49.6	Afrane and Ntiamoah 2011, calculated[2]
Ethanol	27.0	29.7	GREET 2008, MacCarty 2009

Table 2-4. Heating Values of Cooking Fuels in Kenya

Cooking Fuel Type	Lower Heating Value (LHV) MJ/kg	Higher Heating Value (HHV) MJ/kg	Source[1]
Biogas from Dung	17.7	19.4	Afrane and Ntiamoah 2011, calculated[2]
Wood Pellets	16.5	17.8	Jetter et al. 2012

[1] Where two sources are listed, first refers to LHV. Second refers to HHV.
[2] LHV is calculated based on ratio of LHV/HHV for similar fuel as documented in SI1. LHVx = HHVx*(LHVy/HHVy)

Table 2-5. Heating Values of Cooking Fuels in Ghana

Cooking Fuel Type	Lower Heating Value (LHV) MJ/kg	Higher Heating Value (HHV) MJ/kg	Source[1]
Crop Residue	12.8	14.6	Singh et al. 2014a
Firewood	14.0	15.8	Singh et al. 2014a
Charcoal, Average Kiln	25.7	26.2	Afrane and Ntiamoah 2011, calculated[2]
Charcoal, High-Performing Kiln	30.2	31.0	Calculated[3], Pennise et al. 2001
Kerosene	42.9	49.0	Singh et al. 2014a
LPG from Crude Oil	45.8	49.6	Afrane and Ntiamoah 2011, calculated[2]
Ethanol	27.0	29.7	GREET 2008, MacCarty 2009
Biogas from Dung	17.7	19.4	Afrane and Ntiamoah 2011, calculated[2]
Wood Pellets	16.5	17.8	Jetter et al. 2012

[1] Where two sources are listed, first refers to LHV. Second refers to HHV.
[2] HHV is calculated based on ratio of HHV/LHV for similar fuel as documented in SI1. HHVx = LHVx*(HHVy/LHVy)
[3] LHV is calculated based on ratio of LHV/HHV for similar fuel as documented in SI1. LHVx = HHVx*(LHVy/HHVy)

2.1.2 Electricity

The electricity mix for each country is based on the average 2013 electricity mix as reported by the IEA(2013a-d). The electricity modules include estimates of generation, transmission, and distribution losses, which are substantial, and amount to 26, 17, 18, and 26 percent, respectively, for India, China, Kenya, and Ghana. The mix of fuels in the electrical grid is summarized for all four nations in Table 2-6. Potential future changes in the electrical fuel mix are presented in Section 3.2.

Table 2-6. Current Electricity Grids in Covered Countries

Fuels:	2013 India Electrical Grid (%)[1,5]	2013 China Electrical Grid (%)[2]	2013 Kenya Electrical Grid (%)[3]	2013 Ghana Electrical Grid (%)[4]
Coal	72.8	75.5	-	-
Oil	1.94	0.119	30.7	25.6
Natural Gas	5.46	1.66	-	10.4
Biofuels	1.83	0.703	2.02	-
Nuclear	2.87	2.05	-	-
Hydro	11.9	16.9	44.4	64.0
Solar	0.288	0.284	0.011	0.023
Wind	2.81	2.59	0.203	-
Geothermal	-	2.00E-3	22.6	-
Waste	0.112	0.226	-	-
Total Production	**100**	**100**	**100**	**100**
Distribution Losses[6]	**26.0%**	**17.2%**	**18.4%**	**26.7%**

Sources and Notes: [1] IEA 2013a, [2] IEA 2013b, [3] IEA 2013c, [4] IEA 2013d
[5] Percentages based on total Gigawatt hours electricity produced from each fuel.
[6] Calculation: (DS-FC)/DS x 100, where DS = domestic supply and FC = final consumption

India Electricity Grid: As of 2013, coal-fired electricity generation constituted the majority of India's electrical grid, providing over 70 percent of all electricity (Table 2-6). Hydropower and gas comprise twelve and five percent of the grid mix, respectively. Indian distribution losses consume approximately 26 percent of generated electricity.

China Electricity Grid: The electrical fuel mix in China is comprised of just over 75 percent coal with hydroelectric providing a further 17 percent. The remaining five percent of China's electricity grid is generated from a mix of natural gas, nuclear, oil, biomass, and renewables. Electricity losses in the Chinese system amount to 17 percent of generated electricity.

Kenya Electricity Grid: Three fuels supply the majority of Kenyan electricity. Hydroelectric is the largest source of power providing nearly 45 percent of electrical energy. Oil and geothermal provide approximately 31 and 23 percent of electricity, respectively. Kenya is one of a few East African nations that possess significant geothermal resource potential (IRENA 2013). Electricity distribution losses in Kenya total just over 18 percent.

Ghana Electricity Grid: Hydroelectric provides approximately 64 percent of Ghana's electricity. Oil provides a further 26 percent of electricity with the final ten percent being generated by natural gas. Ghana's electrical losses are high, with nearly 27 percent of electricity being lost before reaching the final consumer.

2.1.3 Coal

Coal is a widely used cooking fuel in China with nearly 30 percent of cooking energy being provided by coal powder, coal briquettes, and honeycomb briquettes. Coal sees only limited use in India and is not used in Kenya or Ghana as a cooking fuel at this time.

In India, coal for cookstove use is modeled as produced in an open cast surface mine. Surface mines account for over 80 percent of total coal production in India, and almost 100 percent of the coal grades used for cooking. The consumption of coal for cooking is primarily in areas near coal mines, with an average transport distance of 100 km (rail). Coal is combusted in a metal stove. The coal ash remaining after combustion, as well as the mining overburden, is assumed to be disposed in landfills.

In China, coal is used in a variety of forms, including unprocessed, washed and dried, powdered, formed into briquettes, or formed into honeycomb briquettes. Coal is combusted in metal and brick stoves (both traditional and improved) which have efficiencies assumed to range from 14 percent - 37 percent depending on the fuel/stove technology combination (Zhang et al. 2000). Coal transportation is adapted from the incoming transport within the “hard coal mix at regional storage” unit process from Ecoinvent 2.2. Coal is transported approximately 30 km by barge, 51 km by train, and 100 km by light duty diesel vehicle from the distributor to retail. The coal ash remaining after combustion, as well as the mining overburden, is assumed to be disposed in landfills. The process also includes estimated emissions due to leaching from coal heaps into groundwater at storage sites.

2.1.4 Dung

Dung is a low cost traditional source of cooking fuel in India where it provides over ten percent of cooking energy. Dung is not widely used in the other nations studied. In the LCA model of this study, the dung of stall fed cattle and buffaloes is converted into dung cake primarily by women who mix the manually collected dung with residual feed (e.g., straw, wood chips) (Singh et al. 2014a). Dung cake is combusted in a traditional mud stove with a low thermal efficiency. The remaining ash after combustion is modeled as land-applied. Dung cake is a significant fuel source for cooking only in India. All CO_2 emissions associated with dung cake combustion are assumed to be associated with biogenic carbon and therefore not to contribute to GCCP, as described in Section 4.1.

2.1.5 Crop Residues

Residues from crops such as rice, wheat, cotton, maize, millet, sugarcane, jute, rapeseed, mustard, and groundnut are burned by households in India and China. Crop residues are not used as a cooking fuel in Kenya and contribute less than one percent of cooking energy in Ghana. Country-specific estimates of crop production practices were not developed for the African nations. In India and China, crop residues are modeled as manually collected and air dried but not further processed prior to combustion in cookstoves. In India, 95 percent of crop residues are assumed to be combusted in traditional mud stoves (Smith et al. 2000). In China, 75 percent of crop residues are combusted in improved stoves (IARC 2010), while the remaining crop residues are burned using traditional stove designs. In both countries, the ash remaining after stove use is assumed to be land-applied. The three major biomass crops for India and China are used to estimate the environmental impacts associated with crop production. Rice and wheat are modeled for both countries with the addition of sugarcane and maize for India and China, respectively.

On average in India and China, ten and 29 percent of crop residues are returned to the soil, respectively (IARI 2012, Wang et al. 2013). Additionally, 19 and eight percent of crop residues in India and China are burned in the open on agricultural fields (IARI 2012, Food and Agriculture Organization (FAO)STAT 2016). Emissions associated with field burning of biomass are included in the analysis.

Fertilizer and water use input values are included for each crop. National average estimates of energy and agricultural chemical use are included (FAOSTAT 2016). Emissions of nitrous oxide (N_2O), nitrate, ammonia, and phosphorus are calculated based on fertilizer application rates (Wang et al. 2014, Xia and Yan 2011), with additional values drawn from the literature where available. Methane emissions associated with rice production are estimated using the IPCC method (2006). All CO_2 emissions associated with crop residue combustion are assumed to be associated with biogenic carbon and therefore not to contribute to GCCP, as described in Section 4.1. Detailed documentation of crop production LCI development are available in SI5.

2.1.6 Firewood

Firewood is the predominant cooking fuel in India, Kenya and Ghana where it provides 49, 65, and 46 percent, respectively, of cooking energy. Firewood is also a common cooking fuel in China where it provides 15 percent of total cooking energy demand. Typical tree species used for firewood in India are acacia, eucalyptus, sheesham and mango. In the baseline model, 24 percent of firewood cooking fuel in India is estimated to be non-renewable, based on trends in forest land area, renewable biomass generation on forest land, and demand for cooking firewood as discussed in Section 4.2 (Drigo 2014). In China, cooking firewood is harvested from mature trees or large branches (e.g., eucalyptus, acacia, oak, pine, poplar, and willows), obtained manually from local forest and sun-dried. All carbon in firewood is assumed to come from biogenic sources; however, due to the prevalence of non-renewable forestry practices in the four study nations, not all CO_2 emissions from firewood combustion are considered carbon neutral. The percentage of CO_2 emissions that count towards GCCP is determined by the country specific forest renewability factor, which represents the ability of forests to re-sequester the combusted carbon based on national forest regrowth, as presented in Table 4-1.

Firewood is assumed to be collected manually and combusted using the stove technologies listed in Table 2-8. The remaining ash is assumed to be land applied. Ash production for firewood in Kenya and Ghana is based on an average ash content of 3.3 percent (Afrane and Ntiamoah 2011).

2.1.7 Charcoal

Charcoal in lump form is a widely used cooking fuel in Kenya and Ghana where it provides 17 and 32 percent, respectively, of the current national cooking energy. Charcoal provides approximately one percent of cooking energy in India and is not used in China.

In India, charcoal is produced from wood in a traditional earth mound kiln. The charcoal yield from the kiln is modeled as 30 percent, and kiln combustion residuals are land-applied. The firewood is assumed to be collected and brought to the charcoal kiln manually. Charcoal is modeled as combusted in a metal Angethi stove. Charcoal is an informal manufacturing sector in India, and it is assumed that charcoal is used for cooking only by those living near charcoal kilns (Singh et al. 2014a).

Charcoal in Ghana in the baseline model is produced in an earth mound kiln, with 4.9 kg wood required per kilogram (kg) charcoal output (Afrane and Ntiamoah 2011). Charcoal is assumed to be transported 483 km by single unit truck based on the average distance between forested areas and large urban population centers in Ghana. Charcoal in Kenya is also produced in an earth mound kiln. The dry wood yield of Kenyan kilns is higher than the dry wood yield for Ghana, with 3.2 kg of wood being required per kg charcoal produced (Pennise et al. 2001). Charcoal is transported from the kiln to end users 323 km via single unit truck based on the average distance between forested areas and main population centers in Kenya.

Similar to firewood, all carbon in charcoal is assumed to come from biogenic sources; however, due to the prevalence of non-renewable forestry practices in the four study nations, not all CO_2 emissions from the kiln process and charcoal combustion are considered carbon neutral. The percentage of CO_2 emissions that count towards GCCP is determined by the country specific forest renewability factor, which represents the ability of forests to re-sequester the combusted carbon based on national forest regrowth, as presented in Table 4-1. For all countries with charcoal use, ash remaining after combustion is land applied to nearby agricultural fields.

2.1.8 Liquefied Petroleum Gas

LPG is a common cooking fuel in urban markets in all four study countries. This fuel comprises between 21 and 31 percent of the current cooking fuel mix in India, China, and Ghana. Use of LPG in Kenya is still limited with five percent of cooking fuel energy being provided by this source.

In India, 21 percent of LPG is assumed to be produced from natural gas and 79 percent from crude oil (MPNG 2014). For Indian LPG from natural gas, natural gas extraction is based on drilling, metering, testing and servicing of oil wells and production data of the Oil and Natural Gas Corporation (ONGC), the largest oil company in India. Eighty-four percent of natural gas in India comes from offshore sources and 16 percent is from onshore sources. LPG production is based on the scenario of an LPG production line of the ONGC Uran Gas fractionating plant located near Mumbai, India. Natural gas is transported to the gas fractionating plant by pipeline (500 km from onshore, 250 km from offshore). Processing requirements are allocated to the outputs from LPG production on a direct mass basis. The bottling stage is modeled based on the per-day production scenario of Indian Oil Corporation Limited (IOCL) Barkhola bottling plant located in Assam, India. This plant is one of the recent state-of-the art bottling plants commissioned by IOCL and is considered representative of bottling plants in India. LPG is bottled in steel cylinders (Singh et al. 2014a). Incoming transport of natural gas to the bottling plant is 60 percent by rail (1000 km) and 40 percent by heavy duty vehicle (500 km). The bottled LPG is then transported 750 km by heavy duty diesel vehicle to the distributor and 100 km by light duty diesel vehicle from the distributor to retail.

For the 79 percent of LPG produced from crude oil, the India model considers only the domestic production of refined petroleum fuels. The exclusion of overseas crude oil is not expected to impact findings significantly because only the extraction stage is impacted (not the refining stage), and Indian companies engage in extraction of crude oil following globally accepted practices and operational standards –equivalent to overseas oil companies (Singh et al. 2014a). Onshore crude oil is 30 percent of refinery inputs and is transported 1000 km by rail to the refinery; offshore crude oil makes up 70 percent of the inputs and is first transported 500 km to the port, then 60 percent is transported 1000 km by rail to refineries and 40 percent is transported 500 km to refineries by heavy duty diesel vehicle (Singh et al. 2014a). Mass allocation is used to partition petroleum refining burdens to different refinery products. Once the LPG reaches the bottling plant, the supply chain is equivalent to that modeled for the natural gas LPG supply chain.

LPG production for China is based on two Swiss refineries for the year 2000. Electricity grid mix and rail transport are adapted to the China geographic scope. The bottling stage is simulated based on the model created for India.

LPG in Kenya is modeled as 100 percent derived from crude oil. The crude oil is assumed to be produced in Algeria and transported to Kenya by ship (8,445 km). LPG is bottled in steel cylinders and transported 750 km by truck and 100 km by van within Kenya.

LPG in Ghana is modeled as produced 100 percent from crude oil. The crude oil is produced in Nigeria. LPG is either refined in Nigeria and imported to Ghana, or crude oil is imported to Ghana and the LPG is refined at Ghana's only refinery (Tema Oil Refinery) (Afrane and Ntiamoah 2011). The transport from Nigeria to Ghana is modeled as 433 km by ship. LPG is bottled in steel cylinders and transported 750 km by truck and 100 km by van within Ghana.

2.1.9 Kerosene

Kerosene is used widely in India and Kenya, where it constitutes approximately three and 12 percent of the current cooking fuel mix in each country, respectively. Use of kerosene contributes less than 0.3 percent of cooking energy in both China and Ghana.

For the India kerosene model, only domestic production of petroleum refining products is considered. The exclusion of overseas crude oil is not expected to impact findings significantly because only the extraction stage is affected (not the refining stage), and Indian companies engage in extraction of crude oil following globally accepted practices and operational standards equivalent to overseas oil companies. Onshore crude oil (30 percent of refinery inputs) is transported 1000 km by rail to the refinery; offshore crude oil (70 percent of the inputs) is first transported 500 km to the port, then 60 percent is transported 1000 km by rail to refineries and

40 percent is transported 500 km to refineries by heavy duty diesel vehicle. Mass allocation is used to partition petroleum refining burdens to different refinery products. Thirty percent of kerosene is assumed to be transported 1000 km by rail, while the remaining 70 percent travels the same distance by way of heavy duty diesel vehicle. All kerosene is transported in a light duty diesel vehicle 100 km from the distributor to retail. Similar to LPG, the bottling stage is simulated based on the per-day production scenario of the IOCL Barkhola bottling plant located in Assam, India. Kerosene is bottled in steel cylinders (Singh et al. 2014a).

For China, production of petroleum products is adapted to the China geographic scope using a refinery dataset in Ecoinvent (Ecoinvent Centre 2010). The data set includes all flows of materials and energy for throughput of one kilogram of crude oil in the refinery. The multi-output process 'crude oil, in refinery' delivers the co-products gasoline, bitumen, diesel, light fuel oil, heavy fuel oil, kerosene, naphtha, propane/butane, refinery gas, secondary sulfur, and electricity. The impacts of processing are allocated to the different products on a mass basis. Electricity grid mix and rail transport are adapted to the China geographic scope. The bottling stage is simulated based on the per-day production scenario of the IOCL Barkhola bottling plant located in Assam, India. Kerosene is bottled in steel cylinders. Incoming transport to the bottling plant is 60 percent rail (1000 km) and 40 percent heavy duty vehicle (500 km). All bottled kerosene is modeled as being transported 750 km by heavy duty diesel vehicle to the distributor where it travels a further 100 km by light duty diesel vehicle from the distributor to retail.

Kerosene in Kenya and Ghana is modeled as 100 percent derived from crude oil (Ecoinvent Centre 2010). In Ghana, the crude oil is modeled as produced in Nigeria and shipped to Ghana, where it is refined to kerosene at Ghana's only refinery Tema Oil Refinery (Afrane and Ntiamoah 2011). The crude oil transport from Nigeria to Ghana is modeled as 433 km by ship. For Kenya, the crude oil for kerosene is assumed to be produced in Algeria and transported to Kenya by ship 8,445 km (Ecoinvent Centre 2010). The Ghana kerosene refining process is adapted for Kenya conditions in this study (Afrane and Ntiamoah 2011). For both Kenya and Ghana, the kerosene supply-chain and bottling models are equivalent to those applied for LPG in those countries.

2.1.10 Natural Gas

Natural gas does not currently provide a significant amount of cooking energy in any of the study countries but has the potential to see increased use in the future. Natural gas extraction is based on Russian production data and long-distance pipeline transport of natural gas to China. Energy requirements for operation of the gas pipeline network are adapted from an Italian company data set in Ecoinvent for delivery of natural gas to consumers via pipelines (Ecoinvent Centre 2010). The total leakage rate, modeled as 1.4 percent for long-distance pipeline transport, is based on European data (Ecoinvent Centre 2010). The electricity grid mix and rail transport are adapted for the Chinese and Indian geographic scope.

2.1.11 Coal Gas

Goal gas is produced through coal gasification and delivered directly to consumers via a pipeline network (Zhang et al. 2000). The process technology used in this model, coal gas produced from coke oven gas, is adapted from Ecoinvent for the Chinese geographic scope

(Dones et al. 2007). Coal gas is transport from the plant to rural consumers via a long-distance pipeline network. Coal gas is assumed to be burned in a traditional gas range. Use of coal gas as a cooking fuel in India, Kenya and Ghana is considered unlikely due to the current low prevalence of coal as a heat source for cooking in these countries.

2.1.12 Ethanol

Ethanol is not yet a widely used source of cooking energy in any of the four countries studied. Ethanol is being proposed as a potential clean and efficient source of cooking energy that utilizes agricultural and food waste products widely available in these nations.

Ethanol production and processing in India is modeled based on the data provided by Tsiropoulos and colleagues (2014). In India, sugarcane cultivation practices are almost exclusively manual, with the exception of plowing, which is modeled as partially mechanized in some states. Pre- and post-harvest burning of straw is not practiced in most of India. Sugarcane is transported 12 km by truck to the sugarcane mill. The output products of the conventional sugar mill are sugar, molasses, and electricity from surplus bagasse. Conventional mills represent 75 percent of the sugar production in India. Bagasse provides all necessary energy requirements at the mill as well as surplus electricity, which is considered a useful co-product to replace grid electricity in India. Sugarcane ethanol is then produced from the molasses. This study considers a weighted average of ethanol distilleries as standalone distilleries and as adjacent to sugar refineries. Molasses is transported on average 75 km to the ethanol plant. Sugarcane ethanol production energy is also provided by bagasse. The model is based on a hydrous ethanol yield (for 95 percent ethanol by volume) of 84.7 liters/tonne of cane and an ethanol density of 0.789 kg/L. All ethanol is assumed to be transported 750 km by heavy duty vehicle to the distributor and 100 km by light duty vehicle from the distributor to retail. Sugarcane ethanol combustion emissions are based on laboratory testing rather than field results (e.g., actual measurements from cookstoves in use within India). Sugarcane ethanol production in China is based on the Indian unit process described above, modified for the Chinese electrical grid mix. Ethanol in Kenya is assumed to be produced in India and transported to Kenya (see India model assumptions). Transport to Kenya is modeled as 4,409 km (by ship) based on the distances between major ports in the two countries.

For Ghana, sugarcane ethanol is assumed to be produced in Brazil, the largest global producer of ethanol from sugarcane. Sugarcane production is modeled as 80 percent manual and 20 percent mechanical harvest (Macedo et al. 2008). Ethanol is produced directly from the cane (i.e., cannot be converted first to molasses). Ethanol is produced via a fermentation route using energy from the bagasse. Electricity is co-produced with ethanol, but no credit for exported electricity is applied in the model. Ethanol is transported by ship from Brazil to Ghana (5,177 km).

Sugarcane ethanol combustion emissions are based on laboratory testing. The sugarcane ethanol combustion emission profiles are the same for all countries evaluated (Berick 2006, MacCarty 2009).

2.1.13 Biogas

Biogas sees only modest current use in India and Kenya where it provides less than one percent of cooking energy. This study considers a two-cubic meter household type fixed dome anaerobic digester (AD) operating in continuous feeding mode for 350 days/year and ten years of operational life (UN 2007). The AD is loaded with 19.3 kg/day of fresh dung mixed with small quantities of water to produce 1.31 m^3/day of biogas (Singh et al. 2014a). Leakage is the source of fuel production emissions. Approximately one percent of biogas (CH_4) generated is assumed to leak from the system (Afrane and Ntiamoah 2011, Borjesson 2006). Digested slurry is a useful co-product and is stored for application in land farming. The AD is located at the home where the fuel is used (distributed through piping running from the digester to the home). Feedstock amounts and biogas yields at the household level were available specifically for the Ghana scope based on questionnaires and field measurements within the country (Afrane and Ntiamoah, 2011). Biogas production in China is based on the Indian unit process as described above.

2.1.14 Biomass Pellets

Biomass pellets are not yet widely used as a cooking fuel within any of the countries studied but are proposed as a cleaner and more efficient use of biomass resources (Cashman et al. 2016). Biomass pellets are based on wood feedstock, and forest renewability factors specific to each nation are assumed (Table 4-1). Manual collection and small-scale mechanized pelletization is modeled for all nations using the appropriate national electricity grid (IEA 2013a-d). Pelletization processing energy and distribution transport are adapted from Austria and central Europe (Jungbluth et al. 2007). Incoming transport to pelletization (rail and truck) is included. The inventory for emissions from biomass pellet combustion is based on laboratory testing results. Similar to firewood and charcoal, all carbon in biomass pellets from wood is assumed to come from biogenic sources; however, due to the prevalence of non-renewable forestry practices in the four study nations, not all CO_2 emissions from the pellet combustion are considered carbon neutral. The percentage of CO_2 emissions that count towards GCCP is determined by the country specific forest renewability factor, which represents the ability of forests to re-sequester the combusted carbon based on national forest regrowth, as presented in Table 4-1. Ash remaining following combustion of biomass pellets is disposed of via land application.

2.2 <u>Cookstove Descriptions</u>

The choice of which stove technology to use or to promote, in addition to the selection of the fuel itself, is a critical determinant of the life cycle environmental impacts of an integrated cooking system as was demonstrated in Phase I of this study. This phase incorporates a significant amount of new emissions data for many stove groups, as compared to Phase I, and examines the effect of increased adoption of improved stove technologies alongside shifts in the cooking fuel mix as part of the scenario analysis. Adoption refers to the future use of improved stove technologies or fuel forms in place of current alternatives.

Stove efficiency and emissions data as reported in the literature are always associated with cookstove use in a specific context. That context includes the specific stove model used for the study as well as the fuel type. For each fuel type, there are several parameters that contribute to variation in operational performance. An example of these parameters for firewood would be the heating value associated with a specific tree species or moisture content of the feedstock that is used to perform the study. The laboratory or field testing setup is also a part of the study context and contributes additional uncertainty to the results when they are considered to be representative of national average cookstove use. For this study, individual stove efficiency and emissions results from the literature are grouped together into stove groupings that correspond to the level of detail available on stove use within the nations of study.

Table 2-7 presents stove groupings along with a record of the information that was available for each. A stove group, in this study, is defined by a unique combination of stove type, fuel type, country, and current average efficiency. In the case where a specific country is listed, the average of all available thermal efficiency values was taken as the estimated thermal efficiency that defines that grouping. Thermal efficiency values for the global region are calculated in excel as the 20th percentile value of the sampled thermal efficiencies. While the average was considered as an option for the global region, it was found that this yielded thermal efficiency estimates appreciably higher than those for India and China. This appears to be attributable to a tendency in the literature to focus stove emission testing efforts on more advanced versions of improved cookstoves than on models that are expected to be widely employed in practice. In other words, the availability of global stove emission test results provides more information on emissions from potentially deployable technologies than it does on those in current use. Use of the 20th percentile value is found to produce results that are more in line with those observed for India and China and is believed to be more representative of the stoves used in both Kenya and Ghana.

Table 2-7. Stove Type and Efficiency by Nation

Fuel	Stove Type	Country	Current Efficiency	Efficiency Range	Sample Size (n=)	Source(s)
Hard Coal	Angethi	India	16%	16%	1	1
Coal, Powder	Traditional	China	10%	7-14%	3	8
	Improved	China	17%	17-18%	3	8
Coal, Briquette	Improved	China	32%	27-37%	2	8
Coal, Honeycomb	Traditional	China	20%	16-23%	2	8
	Improved	China	45%	44-47%	2	8
Dung	Traditional	India	9%	8-9%	3	4
	Improved	India	11%	10-13%	2	4
Crop Residue	Traditional	India	11%	10-12%	3	1,4
		China	11%	11%	1	8
		Global[25]	11%	4-18%	6	1,4,8,18
	Improved	India	16%	11-22%	4	4
		China	17%	15-19%	2	9
Firewood	Three-stone	India	18%	17-18%	2	4
		Global	13%	12-15%	4	5,6
	Traditional	India	17%	13-23%	4	1,4,17
		China	12%	12%	1	2
		Global	11%	9-18%	23	2,3,9,15,16
	Improved	India	24%	20-29%	13	2,3,4,17

Table 2-7. Stove Type and Efficiency by Nation

Fuel	Stove Type	Country	Current Efficiency	Efficiency Range	Sample Size (n=)	Source(s)
		China	16%	13-24%	4	8
		Global	19%	11-50%	69	2,5,10,13, 14,15,18, 19,20
Charcoal	Traditional	Global	14%	12-22%	4	2,6,7
	Angethi	India	18%	18%	1	1
	Improved	Kenya	25%	23-27%	4	5
		Ghana	23%	23%	2	5
Kerosene	Improved, Pressure	India	47%	47%	2	1,4
	Improved, Wick	India	50%	50%	1	4
	Improved	China	45%	42-49%	2	8
		Global[25]	46%	37-52%	8	1,4,8,10,2 0,21
LPG	Modern	India	55%	54-57%	2	1,4
		China	47%	42-54%	3	8
		Global[24]	49%	42-75%	11	10,20,21
Natural Gas	Modern	China	57%	54-61%	2	8
Coal Gas	Modern	China	46%	46%	1	8
Electricity	Modern	Global	59%	57-80%	4	11,12
Ethanol	Modern	India	53%	53%	1	21
		Kenya	46%	40-52%	2	10
		Global	49%	43-66%	4	10
Biogas	Modern	India	56%	55-57%	2	1,4
	Modern	China	56%	55-57%	2	1,4
	Modern	Global	55%	32-57%	5	1,21
Pellet, Wood	Modern	Global	35%	35-53%	6	5, 23

Sources and Notes: [1] Singh et al. 2014a/b, [2] Bhattacharya et al. 2002b, [3] Bhattacharya et al. 2002a, [4] Smith et al. 2000, [5] Jetter et al. 2012, [6] Sweeney 2015, [7] Booker 2012, [8] Zhang et al. 2000, [9] Afrane and Ntiamoah 2012, [10] GACC 2016, [11] Schaetzke 1995, [12] EC 2011 [13] Jetter and Kariher 2009, [14] Winrock 2009, [15] AED 2008, [16] AED 2007, [17] Bailis et al. 2007, [18] Collivignarelli et al. 2010, [19] Robinson 2013, [20] MacCarty et al. 2010, [21] CES 2001, [22] Berick 2006, [23] Carter et al. 2014

[24] Current average thermal efficiency set as the average of India/China (IN/CN) due to the wide range of reported values, which skew towards high thermal efficiency.

[25] Average of reported thermal efficiencies used to derive current thermal efficiency, as opposed to 20th percentile, due to the presence of low values and a better match with the IN/CN average.

The following sections outline stove characteristics considered for each country and the methodology and data sources used to compile emissions data and assemble cookstove LCIs.

2.2.1 Stove Efficiency

As is indicated in the preceding section, the records of stove emissions and performance included in this study exhibit a range of thermal efficiency values for each fuel. The Phase I LCA for China and India indicated that stove thermal efficiency is a driving parameter for the overall life cycle environmental impacts of cookstove fuels (Cashman et al. 2016). Stove efficiency not only affects the emissions at point of use but also the overall fuel quantity required to produce the functional unit. Changes in the fuel quantity required to deliver 1 GJ of energy to the pot impact all upstream life cycle stages (e.g., higher stove thermal efficiencies result in less fuel being extracted, processed, and transported). Figure 2-1 presents a box plot depicting the range of thermal efficiency values for each fuel type as compiled from the literature. Figure 2-1 also displays the average current thermal efficiency value for fuels by country used in the baseline model when applicable. These presented ranges incorporate both improved and traditional stoves. Stove technology use by country is covered in subsequent sections. Documentation of values and references used to create this figure are available in Table 2-7 and SI1.

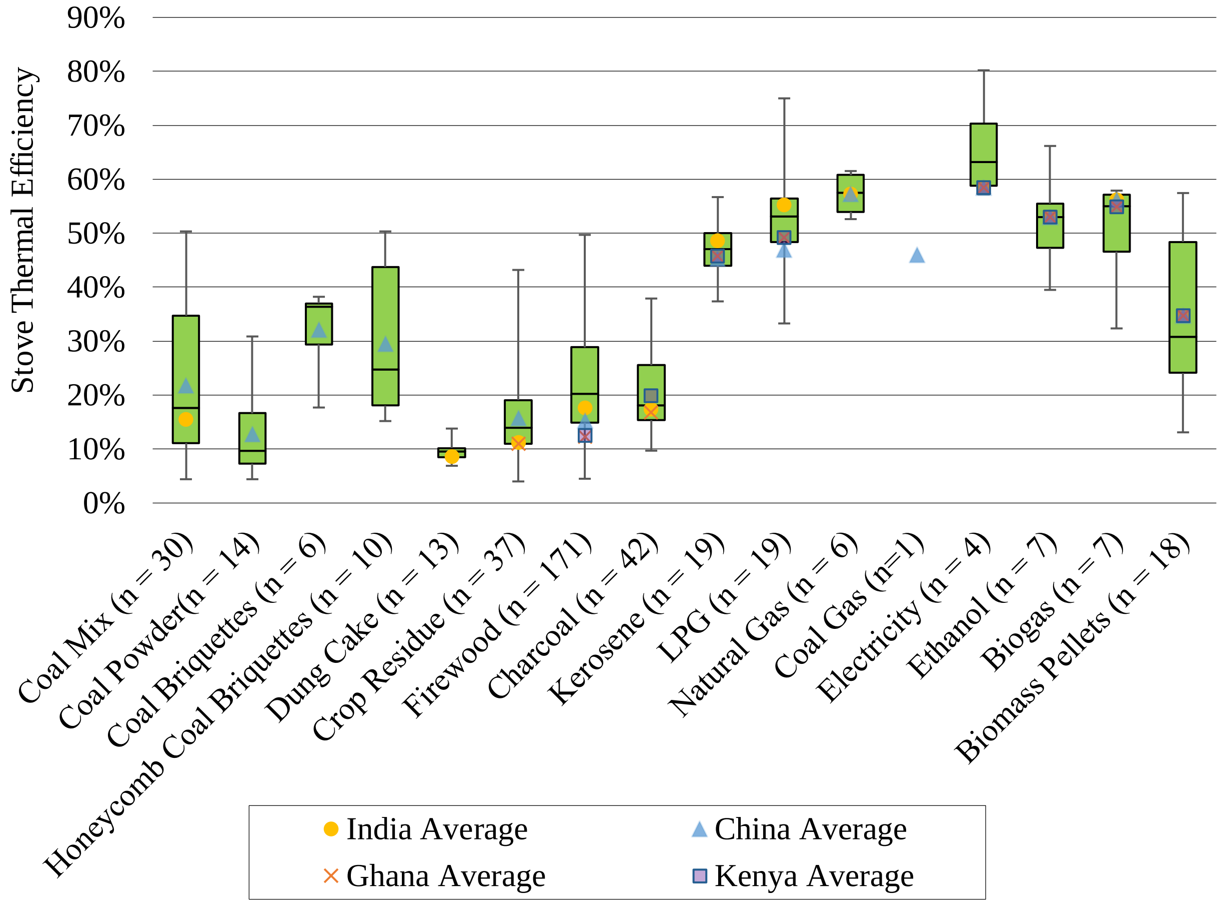


Figure 2-1. Range of reported stove thermal efficiencies by cooking fuel type.

2.2.2 Stove Technology Use by Country

The rate of adoption of improved cookstoves and the specific model of cookstove used varies widely between nations. This section presents the current use of traditional, improved, and modern cookstove technologies to provide cooking energy by fuel type in India, China, Kenya, and Ghana. Table 2-8 presents this information along with the national average thermal efficiency value for each fuel, which is a weighted average of stove thermal efficiency associated with underlying stove technology use. Stove technology use for each country was adapted from the references listed in Table 2-8. Assumptions based on noted references used to develop the documented stove technology mixes are documented in SI1. Information pertaining to current national stove technology use was found to be limited, see Appendix C for more detail on related stove technology use data quality considerations.

Table 2-8. Stove Technology Use and Aggregate Thermal Efficiency by Fuel (Stove Technology Use is Presented as a Fraction of National Cooking Energy)

Fuel	Stove Type	Stove Use Technology Use				Aggregate Efficiency[1]			
		India[1]	China[2 4]	Kenya[5 9]	Ghana[10 12]	India	China	Kenya	Ghana
Coal	Traditional	1.2%	17.9%	-	-	15.5%	21.8%	-	-
	Improved	-	11.0%	-	-				
Dung	Traditional	10.0%	-	-	-	8.7%	-	-	-
	Improved	0.6%	-	-	-				
Crop Residue	Traditional	8.4%	2.8%	-	0.4%	11.4%	15.8%	-	-
	Improved	0.5%	9.2%	-	-				
Firewood	Three-stone	4.6%	-	51.9%	36.7%	17.5%	17.5%	13.5%	13.5%
	Traditional	41.5%	3.4%	11.5%	9.2%				
	Improved	2.9%	11.3%	1.5%	-				
Charcoal	Traditional	1.2%	-	7.6%	20.3%	17.5%	-	20.0%	16.9%
	Improved	-	-	9.3%	11.2%				
Kerosene	Pressure	1.5%	-	-	-	48.6%	45.3%	45.9%	45.9%
	Wick	1.7%	-	-	-				
	Improved	-	0.3%	11.6%	0.2%				
LPG	Modern	25.2%	33.5%	5.0%	21.7%	55.3%	47.0%	49.2%	49.2%
Electricity	Modern	0.4%	10.6%	0.8%	0.3%	58.5%	58.5%	58.5%	58.5%
Biogas	Modern	0.4%	-	0.7%	-	56.2%	47.6%	47.6%	47.6%
Total		100%	100%	100%	100%				

Sources and Notes: [1] Smith et al. 2000, [2] IARC 2010, [3] Dalberg 2014, [4] NBSC 2008, [5] Githiomi et al. 2012, [6] SEI 2016, [7] Dalberg 2012, [8] Clough 2012, [9] Dalberg 2013a, [10] Energica 2009, [11] GLSS6 2014, [12] ADP 2012
[13] For efficiency of a particular stove-fuel combination see Table 2-7

India: Nearly 50 percent of cooking energy in India is derived from firewood, and over 85 percent of this cooking is done using traditional mud stoves. Improved woodstoves have not yet been widely adopted, representing less than three percent of total cookstove use. Traditional mud stoves are also the main combustion technology used for cooking with both dung cake and crop residues. Dung burned in traditional stoves exhibits the lowest thermal efficiency of all stove-fuel combinations at just nine percent. Coal and charcoal are assumed to be burned in the traditional Angethi stove, which has a reported thermal efficiency of 15 and 18 percent for the two fuels, respectively. Among kerosene users in India there is a relatively even split between the use of wick and pressure stoves. LPG, electricity, and biogas are all burned in modern stoves.

China: The International Agency for Research on Cancer (IARC 2010) conducted a survey in rural China finding that 77 percent of biomass stoves are classified as improved. The remaining 23 percent of biomass is burned in traditional stoves with an average thermal efficiency of only twelve percent. Thirty-eight percent of coal is burned in improved cookstoves with the remaining 62 percent of this feedstock being burned in traditional cookstoves. These percentages are applied to all forms of coal-based fuel including powder, briquette, and honeycomb briquette. Kerosene, LPG, electricity, and biogas are all burned in modern stoves.

Kenya: Approximately 52 percent of all Kenyan households cook their meals with wood fuel over an open three-stone fire, which constitutes 80 percent of firewood users. A further 18 percent of firewood is consumed in traditional stoves, signaling very limited adoption of improved wood stoves in Kenya. Improved cookstoves occupy a larger proportion of the charcoal market where they are used preferentially in urban areas, providing 55 percent of cooking energy from this fuel source. Kerosene, LPG, electricity, and biogas are all burned in modern stoves with thermal efficiencies above 45 percent.

Ghana: Over 65 percent of charcoal cooking is done in a traditional stove known as a coal pot. The coal pot is simple in design consisting of an open vessel on a base into which the charcoal is placed. The vessel has a slotted bottom for air flow and the cooking pot is placed directly on the charcoal for cooking. Firewood is also used heavily in Ghana with nearly all users burning firewood over a traditional three-stone fire or mud stove. Crop residue is used only marginally and is assumed to be consumed using traditional stoves. Kerosene, LPG, and electricity are all burned using modern stoves with thermal efficiency values between 46 and 59 percent.

2.2.3 Stove Emissions Data Sources and Methodology

Stove emissions data from the literature were compiled into LCI unit processes according to the groupings established in Table 2-1. Sufficient information was found to create country-specific stove emissions and efficiency data for both India and China. Information specific to Kenya and Ghana was limited and for most stove groupings, it was necessary to use the average of the remaining data discovered for developing countries as a proxy. In a few cases, this averaging was also necessary for India and China. The averaging was done in the interest of including the full breadth of possible emissions and efficiency data. The stove emission profiles for Kenya and Ghana are not specific to those nations; however, this generalized stove emission information was incorporated into upstream fuel production, fuel mix, and stove technology use scenarios that are specific to both countries. A sample of selected representative stove emissions is provided in Table 2-9. The references cited in the table are sources of information used for the full stove LCI, and not all references contain a record for each individual pollutant species.

An extensive database of all stove emission information was compiled and reviewed according to the project QAPP. This database was filtered according to the criteria that define the established groups: (1) country, (2) fuel type, and (3) stove type. All data fields for which an emission value is present were extracted from the database and used as the basis of LCI emissions, which are documented in SI2. Stove thermal efficiency and fuel heat content are used to transform emission values that are reported on the basis of fuel consumed (e.g., g/kg) and not on the basis of delivered heat. Where possible, these values were drawn from the original study itself and are reported in the database. In cases where the original study does not report either stove thermal efficiency or fuel heat content, the average of all reported values that correspond to a specific stove group was used in the calculation.

To ensure a fair comparison of environmental impacts among different stoves, fuels, or countries, it is important that the same scope of inputs and emissions be considered across options. This type of comparison requires a line to be walked between inclusion of the most detailed available information, which may be available only for certain stoves, fuels, or countries, and a desire to establish fair comparisons between stove groups and countries. With this interest in mind, the authors identified a list of key pollutants that are necessary to ensure a complete inventory for each stove grouping. These pollutants include: CO_2, CH_4, N_2O, CO, NOx, SO_2, PM, NMVOCs, and ash. BC emissions are estimated on the basis of PM emissions as described in Section 4.3. Other emissions are included in the LCI for each stove, when available, but these emissions are not necessarily available for all stove groupings. To ensure that the full inventory of priority pollutants is present for each stove grouping, it has been necessary in some instances to use records of pollutant emissions from other countries or the closest available stove grouping to fill holes in some of the stove emission inventories. A record of precisely what emissions are included or excluded for each stove group and the source of proxy emission values is available in Appendix C and SI2. A discussion of the approach to estimating stove emission uncertainty is included in Section 4.5.1.

Table 2-9. Summary Table Showing Representative Stove Emissions

Stove Grouping	Country	CO_2	CO	PM (>2.5<10)	CH_4	NOx	SO_2	Source(s)
Coal Powder, Traditional	China	979	38	2.5	3.9	0.93	4.90	3,10
Coal Powder, Improved	China	642	32	0.8	0.7	0.3	0.1	3,10
Coal Briquette, Improved	China	364	4.5	0.03	0.00	0.1	0.3	3,10
Honeycomb Coal, Traditional	China	326	17	no estimate	no estimate	no estimate	no estimate	3,10,13,14
Honeycomb Coal, Improved	China	284	7.3	0.5	0.4	0.1	0.1	3,10,15
Dung Cake, Traditional	India	991	51	23	9.7	0.8	0.3	1,2,3,6
Dung Cake, Improved	India	800	23	no estimate	2.6	0.2	no estimate	3,6
Crop Residue, Traditional	India	806	39	11	4.2	0.8	0.2	1,2,3,6
Crop Residue, Traditional	China	892	73	4.9	no estimate	no estimate	no estimate	3,9,13
Crop Residue, Improved	India	480	37	no estimate	4.2	0.1	no estimate	3,6
Crop Residue, Improved	China	539	47	4.9	2.0	0.6	0.04	3,10,11,12,16,17
Firewood, three-Stone	India	534	22	no estimate	2.2	0.05	no estimate	3,6
Firewood, Traditional	India	614	32	4.6	1.8	0.4	0.2	1,2,3,6
Firewood, Traditional	China	660	31	1.2	2.3	0	no estimate	4,3,8,9
Firewood, Improved	India	358	19	no estimate	2.1	0	no estimate	3,4,5,6
Firewood, Improved	China	606	34	1.5	1.4	0.5	0.01	3,10,11,12
Charcoal, Improved	Kenya	337	28	0.5	2.0	no estimate	no estimate	7
Charcoal, Improved	Ghana	346	36	0.9	1.7	no estimate	no estimate	7
Kerosene, Modern, Pressure	India	145	2.9	no estimate	0.1	0.01	no estimate	3,6
LPG, Modern	India	126	0.6	no estimate	0.00	0.01	no estimate	3,6
LPG, Modern	China	146	0.3	no estimate	0.02	0.0	0.00	3,10
Biogas, Modern	India	144	0.2	0.2	0.1	0.01	0.1	1,3,6

Sources: [1] Singh et al. 2014a,b, [2] Saud et al. 2012, [3] Zhang et al. 1999, [4] Bhattacharya et al. 2002b, [5] Bhattacharya et al. 2002a, [6] Smith et al. 2000, [7] Jetter et al. 2012, [8] Shen et al. 2013, [9] Shen et al. 2012b, [10] Zhang et al. 2000, [11] Shen et al. 2012a, [12] Wang et al. 2009, [13] Shen et al. 2010b, [14] Shen et al. 2010a, [15] Zhi et al. 2008, [16] Cao et al. 2008, [17] Wei et al. 2014, [18] Sweeney 2015

3. METHODOLOGY FOR SCENARIO DEVELOPMENT AND SENSITIVITY ANALYSES

3.1 Cooking Fuel Mix Scenario Development

As a result of Phase I, it was determined that differences in environmental impact that existed between individual cooking fuels were greater than the differences in environmental impact realized between the fuel mix scenarios analyzed, indicating that more dramatic departures from the current fuel mix than were explored in Phase I may be required to realize appreciable environmental gains. Given this, a Diverse Modern Fuel scenario has been developed for each country, which represents a relatively dramatic departure from the status quo. The remaining three fuel mix projections are based both on literature sources and analysis of past trends in fuel mix development as recorded in SI3. Notable sources used to construct the future cooking fuel mix scenarios include government surveys, IEA World Energy Outlook reports, and other peer-reviewed studies. Result files for each country allow users to specify a custom fuel and stove technology mix based on their own understanding of potential developments in the cooking sector for each nation.

Underlying the potentially dramatic shifts in cooking fuel mix over the next 20 to 30 years are a series of major socioeconomic changes. Both India and China are experiencing a period of rapid economic expansion, with rates of gross domestic product (GDP) growth exceeding seven percent per annum. GDP growth rates in Kenya and Ghana are appreciably lower at approximately five and four percent, respectively (World Bank 2014a). The population of all four nations is expected to expand over this period, with India projected to become the most populous country in the world sometime between 2030 and 2040. Currently, the population of India is 1.25 billion and is expected to grow to 1.6 billion people by 2040. The Chinese population is now over 1.35 billion and will top 1.5 billion by the year 2030. While Kenya and Ghana’s total populations are significantly lower at approximately 44 and 26 million, respectively, they each exhibit growth rates of greater than two percent (World Bank 2014b,c).

Access to electricity within the four countries also varies dramatically. China reports that over 99 percent of the population currently has access to electricity (IEA 2007). However, only 79 percent of the Indian population and 64 percent of Ghana’s population have access to this basic service. Access within Kenya is particularly low with an electrification rate of only 23 percent (World Bank 2012). By 2030, 96 percent of India is projected to have access to electricity; reliability should increase dramatically, and losses in the electricity grid are expected to fall (IEA 2007). The governments of both Kenya and Ghana also have plans to dramatically increase generation capacity.

Within the context of economic and population growth and development lies a dynamic landscape of fuel resources and relative fuel costs. It is well understood that as incomes rise, the reliance on traditional, solid biomass fuels begins to fall in favor of more convenient liquid and gas options (Malla and Timilsina 2014). Advanced biomass may also provide an attractive alternative if adequate supply chains can be established that provide for much of the convenience of other advanced fuel options while still retaining a traditional character and flavor.

Assumptions regarding the increased uptake of improved stove types and advancements in thermal efficiency are applied to future cooking fuel scenarios as a form of sensitivity analysis. This aspect of the present study affords a better understanding of the potential gains to be made by fuel mix substitutions versus adoption of more advanced stove technologies. Values describing current and future cookstove technology use scenarios are presented in Table 3-1 through Table 3-4 for India, China, Kenya, and Ghana, respectively.

References for current stove use and current thermal efficiency values can be found in Table 2-7 and Table 2-8. Future stove use scenarios assume that 100 percent of cooking fuels are burned in either improved or modern cookstove designs. This assumption serves as an upper bound regarding the possible adoption of improved technologies. The proposed future thermal efficiency is assumed equal to the maximum reported stove thermal efficiency value for each stove group.

Table 3-1. Adoption of Improved Stove Technologies and Thermal Efficiency in India

Fuel	Stove Type	Current Stove Use[1]	Future Stove Use	Current Thermal Efficiency[2]	Future Thermal Efficiency[2]
Coal	Traditional	100%	100%	16%	16%
Dung	Traditional	95%	0%	9%	9%
	Improved	5%	100%	11%	13%
Crop Residue	Traditional	95%	0%	11%	12%
	Improved	5%	100%	16%	22%
Firewood	Three-stone	9%	0%	18%	18%
	Traditional	85%	0%	17%	23%
	Improved	6%	100%	24%	29%
Charcoal from Wood	Traditional	100%	0%	18%	18%
Kerosene	Improved, Wick	54%	54%	50%	50%
	Improved, Pressure	46%	46%	47%	47%
LPG	Modern	100%	100%	55%	57%
Natural Gas	Modern	-	100%	-	61%
Electricity	Modern	100%	100%	59%	80%
Sugarcane Ethanol	Modern	100%	100%	-	53%
Biogas	Modern	-	100%	-	56%
Biomass Pellets	Modern	-	100%	-	53%

[1] Estimates of current stove technology use adapted from Smith et al. 2000
[2] Supporting documentation and calculations available in SI1.

Table 3-2. Adoption of Improved Stove Technologies and Thermal Efficiency in China

Fuel	Stove Type	Current Stove Use	Future Stove Use	Current Thermal Efficiency[1]	Future Thermal Efficiency[1]	Current Stove Use Reference[2]
Coal, Powder	Traditional	62%	0%	10%	14%	IARC 2010
	Improved	38%	100%	17%	17%	IARC 2010
Coal, Briquette	Improved	100%	100%	32%	37%	-
Coal, Honeycomb	Traditional	62%	0%	20%	23%	IARC 2010
	Improved	38%	100%	45%	47%	IARC 2010
Crop residue	Traditional	23%	0%	11%	11%	IARC 2010
	Improved	77%	100%	17%	19%	IARC 2010
Firewood	Traditional	23%	0%	12%	12%	IARC 2010
	Improved	77%	100%	16%	24%	IARC 2010
Kerosene	Improved	100%	100%	45%	49%	-
LPG	Modern	100%	100%	47%	54%	-
Natural Gas	Modern	100%	100%	57%	59%	-
Coal Gas	Modern	-	100%	-	46%	-
Electricity	Modern	100%	100%	59%	80%	-
Sugarcane Ethanol	Modern	-	100%	-	53%	-
Biogas	Modern	-	100%	-	56%	-
Biomass Pellets	Modern	-	100%	-	53%	-

[1] Supporting documentation and calculations available in SI1.
[2] Estimates of current stove technology use adapted from the listed reference(s)

Table 3-3. Adoption of Improved Stove Technologies and Thermal Efficiency in Kenya

Fuel	Stove Type	Current Stove Use	Future Stove Use	Current Thermal Efficiency[1]	Future Thermal Efficiency[1]	Current Stove Use Reference[2]
Firewood	Three-stone	80.0%	0%	13%	15%	Githiomi et al. 2012, SEI 2016
	Traditional	17.7%	0%	11%	18%	Dalberg 2012
	Improved	2.3%	100%	19%	27%	Clough 2012
Charcoal	Traditional	45%	0%	14%	18%	Clough 2012
	Improved	55%	100%	25%	26%	Clough 2012
Kerosene	Improved	100%	100%	52%	52%	-
LPG	Modern	100%	100%	49%	53%	-
Electricity	Modern	100%	100%	59%	69%	-
Sugarcane Ethanol	Modern	-	100%	-	53%	-
Biogas	Modern	100%	100%	48%	52%	-
Biomass Pellets	Modern	-	100%	-	53%	-

[1] Supporting documentation and calculations available in SI1.
[2] Estimates of current stove technology use adapted from the listed reference(s)

Table 3-4. Adoption of Improved Stove Technologies and Thermal Efficiency in Ghana

Fuel	Stove Type	Current Stove Use	Future Stove Use	Current Thermal Efficiency[1]	Future Thermal Efficiency[1]	Current Stove Use Reference[2]
Crop Residue	Traditional	100%	0%	11%	18%	-
Firewood	Three-stone	80%	0%	13%	15%	Energica 2009
	Traditional	20%	0%	11%	18%	Energica 2009
	Improved	0	100%	-	27%	Energica 2009
Charcoal	Traditional	64%	0%	14%	22%	Energica 2009
	Improved	36%	100%	23%	23%	Energica 2009
Kerosene	Improved	100%	100%	46%	52%	-
LPG	Modern	100%	100%	49%	55%	-
Electricity	Modern	100%	100%	59%	80%	-
Sugarcane Ethanol	Modern	-	100%	-	53%	-
Biogas	Modern	100%	100%	48%	52%	-
Biomass Pellets	Modern	-	100%	-	53%	-

[1] Supporting documentation and calculations available in SI1.
[2] Estimates of current stove technology use adapted from the listed reference(s)

3.1.1 India Cooking Fuel Mix Scenarios

Table 3-5 provides a name and basic description for each of the five cooking fuel mix scenarios developed for India. Table 3-6 introduces the cooking fuels that comprise each scenario and compares those values to the baseline (current) cooking fuel mix. A full description of each scenario is provided in the subsections that follow. Details regarding fuel mix development and documentation are available in SI3.

Table 3-5. Cooking Fuel Mix Scenario Names and Descriptions for India

Scenario	Scenario Name	Scenario Description
(1)	Current	Current fuel mix, recent year
(2)	BAU 2040	Projected 2040 fuel mix adapted from IEA 2015
(3)	Improved Biomass	Assumes increased use of improved biomass options such as biogas, biomass pellets, and ethanol
(4)	Increased Electricity	Electricity use displaces the use of LPG, kerosene, and the traditional biomass fuels
(5)	Diverse Modern Fuels	Promotes a balanced use of modern fuels and improved stove technologies

Table 3-6. Cooking Fuel Mix Scenarios Evaluated for India

Fuel Type	Current (1)[1,2]	BAU 2040 (2)[3]	Improved Biomass (3)[4]	Increased Electricity (4)[4]	Diverse Modern Fuels (5)
Hard Coal	1.2%	0.80%	0.90%	0.90%	-
Dung Cake	11%	4.5%	2.8%	2.2%	1.0%
Crop Residue	8.9%	3.8%	2.0%	1.6%	1.0%
Firewood	49%	21%	13%	17%	5.0%
Charcoal from Wood	1.2%	3.3%	6.6%	3.3%	6.6%
Kerosene	3.2%	-	2.0%	6.0%	-
LPG	25.2%	52%	48%	38%	38%
Natural Gas	-	6.8%	-	-	3.0%
Electricity	0.40%	3.2%	8.4%	25%	20%
Sugarcane Ethanol	-	-	6.0%	-	6.0%
Biogas from Cattle Dung	0.40%	2.2%	4.4%	2.2%	4.4%
Biomass Pellets	-	3.3%	6.6%	3.3%	15%
TOTAL[4]	100%	100%	100%	100%	100%

Sources: [1] Dalberg 2013b, [2] Venkatarman et al. 2010, [3] IEA 2015, [4] IEA 2007
[4] Columns may not total 100 due to rounding, unrounded numbers available in SI

3.1.1.1 Current Fuel Mix (India Cooking Fuel Mix Scenario 1)

The current cooking fuel mix estimate for India is based on 2011 census data collected by the Government of India. Nearly 70 percent of India's population, mostly in rural areas, still rely on dung, crop residues, and firewood to provide their cooking energy. Firewood contributes just over 49 percent of the total cooking fuel mix, while dung and crop residues contribute eight and nine percent, respectively. Coal and charcoal together make up only 2.4 percent of the cooking fuel mix. LPG is used extensively at the national level, providing cooking energy for approximately 25 percent of households. Kerosene is used in much more limited quantities (three percent of the fuel mix). Unlike China, electricity is used only sparsely, providing 0.4 percent of cooking energy.

3.1.1.2 Potential Future Scenarios

Business-as-Usual (BAU) 2040 (India Cooking Fuel Mix Scenario 2)

The IEA projected cooking fuel mix for 2040 sees a 45 percent decrease in reliance on biomass fuels as compared to the current baseline scenario. Traditional fuels are expected to comprise under 30 percent of the overall fuel mix. The IEA reference does not specify the type of traditional fuel, so the original ratios of coal, firewood, crop residue, and dung use have been maintained and applied to the lower percentage of cooking energy provided by traditional fuel sources. Reliance on direct combustion of fossil fuels nearly doubles, in this scenario, increasing to comprise 59 percent of the fuel mix. LPG provides the majority of fossil-based heat with a seven percent contribution from natural gas, a fuel that was not considered in the Phase I study. Electricity use increases by a factor of eight but still provides only three percent of the fuel mix (IEA 2015).

Improved Biomass (India Cooking Fuel Mix Scenario 3)

The Improved Biomass scenario is adapted from the IEA's cooking energy projections for the year 2030 (IEA 2007). The original IEA 2030 fuel mix is similar to the fuel mix projected by the IEA for the year 2040 (IEA 2015), with a higher expectation for the increased use of electricity. In the IEA 2030 scenario, reliance on electricity as a cooking fuel rises to just over eight percent. The original values projected by IEA have been adjusted to provide greater differentiation with the 2040 scenario, exploring the effect of a more aggressive transition from traditional to improved biomass sources. Expectations for LPG use have been maintained as provided in the original scenario, with 47 percent of the fuel mix being provided by LPG. The original IEA scenario values suggested that kerosene would rise to constitute eight percent of the cooking fuel mix. This scenario assumes that the use of sugarcane ethanol will instead increase to six percent of the cooking fuel mix, thereby leaving kerosene to contribute near its current level of use. Assumed contributions from biogas, charcoal, and biomass pellets have doubled in comparison to the 2040 scenario with fuel mix contributions of 4.4, 6.6, and 6.6 percent, respectively. These increases are offset be a decreased reliance on firewood, crop residue, and dung cake. Together, these three fuels constitute approximately 18 percent of the fuel mix.

Increased Electricity (India Cooking Fuel Mix Scenario 4)

The Increased Electricity scenario is based on a combination of the IEA 2030 and 2040 projections. However, with electricity access expanding to 96 percent of the population by 2030, this scenario was developed to explore the effect of greater adoption of electric stove technology than the IEA is projecting. The likelihood of this switch depends on the relative cost of electricity versus other advanced fuel options, particularly LPG. In this scenario, it is assumed that the projected increase in LPG and Kerosene use is reduced by 20 percent with the difference being made up by the adoption of electric stoves. Reliance on the traditional biomass fuels is also decreased by nearly ten percent in favor of electricity and kerosene use. Kerosene use is set at six percent of the cooking mix in this scenario. Levels of advanced biomass use associated with the IEA 2040 scenario are maintained here, with low reliance on crop residue and dung cake from the 2030 scenario. Overall, electricity makes up just over 25 percent of the cooking fuel mix in this scenario.

Diverse Modern Fuels (India Cooking Fuel Mix Scenario 5)

The Diverse Modern Fuels scenario presents a dramatic departure from the current cooking energy mix, which takes cues from the LCA results that came out of the Phase I study. The LCA fuel results showed that both biogas and biomass pellets were the best performing cooking fuels in most impact categories. LPG also performed relatively well, especially in the PM and BC impact categories, which are so crucial to human health. LPG is also an incredibly convenient fuel with an attractive package of incentives being offered by the Government of India. LPG is expected to comprise a large portion of any future cooking fuel mix. Together, LPG and natural gas contribute 41 percent of the cooking fuel mix in the Diverse Modern Fuels scenario. It is assumed that 20 percent of the cooking fuel mix is provided by electricity. Biogas and charcoal are adopted at the same rate as specified in the Improved Biomass scenario. The main difference from the other scenarios is the dramatic adoption of pelletized biomass fuel, which increases to provide 15 percent of the cooking fuel mix. The potential economic savings of a switch from LPG to biomass pellets has been demonstrated in some contexts (Thurber et al.

2014). It is assumed that a minimum amount of firewood, crop residue, and dung use will continue past 2030. The minimal amount of coal use that previously existed is eliminated entirely.

3.1.2 China Cooking Fuel Mix Scenarios

Table 3-7 provides a name and basic description for each of the five cooking fuel mix scenarios for China. Table 3-8 introduces the cooking fuels that comprise each scenario and compares those values to the current cooking fuel mix. No more recent values for the cooking fuel mix were able to be found since the release of the Phase I study, so the Phase I and Phase II current fuel mix estimates are identical. A full description of each scenario is provided in the subsections that follow. Details regarding fuel mix development and documentation are available in SI3.

Table 3-7. Cooking Fuel Mix Scenario Names and Descriptions for China

Scenario	Scenario Name	Scenario Description
(1)	Current	Current fuel mix, recent year
(2)	BAU 2030	2030 BAU cooking fuel projections
(3)	Increased Electricity	Electricity use displaces the use of LPG and Coal
(4)	Advanced Biomass and Electricity	Coal use offset by adoption of electricity and advanced biomass technology
(5)	Diverse Modern Fuels	Promotes a balanced use of modern fuels and improved stove technologies

Table 3-8. Cooking Fuel Mix Scenarios Evaluated for China

Fuel Type:	Current (1)[1,2]	BAU 2030 (2)[3]	Increased Electricity (3)[3]	Advanced Biomass & Electricity (4)[3]	Diverse Modern Fuels (5)[3]
Coal	29%	24%	12%	15%	5.9%
Coal Powder	14%	12%	5.9%	7.3%	3.0%
Coal Briquettes	7.2%	5.9%	3.0%	3.6%	1.5%
Honeycomb Briquettes	7.2%	5.9%	3.0%	3.6%	1.5%
Crop Residue	12%	5.2%	5.2%	2.0%	-
Firewood	15%	6.4%	6.4%	2.4%	-
Kerosene	0.30%	-	-	-	-
LPG	31%	45%	38%	33%	46%
Natural Gas	2.4%	-	-	-	15%
Coal Gas	-	12%	12%	9.3%	2.9%
Electricity	11%	8%	27%	19%	15%
Biogas	-	0.62%	0.60%	6.0%	6.0%
Biomass Pellets	-	-	-	13%	9.0%
TOTAL[3]	*100%*	*100%*	*100%*	*100%*	*100%*

Sources: [1] Dalberg 2014, [2] NBSC 2008, [3] adapted from Mainali et al. 2012
[3] Columns may not total 100 due to rounding, unrounded numbers available in SI

3.1.2.1 Current Baseline Scenario (China Cooking Fuel Mix Scenario 1)

The current fuel mix scenario for China is the same as the scenario used in the Phase I report. More than half of China's population, mostly in rural areas, still rely on traditional solid fuel feedstock for their cooking needs. The current fuel mix in China is dominated by the use of three fuels: LPG, coal, and biomass. Each of these fuels comprises slightly less than one third of the total fuel use. Nearly 11 percent of the population uses electricity as a cooking fuel. Only a small percentage of the population uses kerosene or natural gas.

3.1.2.2 Potential Future Scenarios

BAU 2030 (China Cooking Fuel Mix Scenario 2)

The 2030 projections are a BAU scenario that projects no major policy changes out to the year 2030. Despite this conservative approach, the BAU 2030 cooking fuel mix is dramatically different from the cooking fuel mix that existed in 2005, the beginning of the author's study period (Mainali et al. 2012). By 2030, biomass (firewood and crop residues) are expected to contribute only a combined nine percent of the cooking fuel mix. Reductions in coal use are far less substantial. Still nearly a quarter of cooking energy is provided by some form of coal. Coal gas is expected to provide 12 percent of cooking energy, particularly in urban areas where it is distributed via pipeline. LPG use increases to provide 45 percent of cooking energy, while electricity use holds flat at approximately ten percent. Biogas is expected to contribute a small portion, 0.6 percent, of cooking energy in rural areas.

Increased Electricity (China Cooking Fuel Mix Scenario 3)

The Increased Electricity scenario examines the effect of more widespread adoption of electricity for household cooking. There are two major factors providing a rationale for this scenario. The first is the existing presence of nearly universal access to electricity resources throughout urban and rural China (World Bank 2012). The second factor is the observation of the 2030 BAU scenario that shows a continued, significant reliance on coal energy for cooking in both urban and rural households. There is little indication in the literature that China has plans of dramatically scaling back coal production in the foreseeable future. In fact, the majority of grid projections in China for the period 2030 to 2050 rely on coal for between 47 and 73 percent of electrical energy. There is, however, a possibility that China will pursue an aggressive upgrade of their coal electricity generating technology, with the possible inclusion of carbon capture and sequestration (IEA 2010, Zhou et al. 2011). Advanced coal burning technologies such as supercritical generators and Integrated Gasification Combined Cycle (IGCC) coal plants have the potential to reduce coal use while simultaneously cutting harmful air emissions. This cooking fuel scenario assumes that 27 percent of cooking energy is supplied by electricity. This shift allows a 50 percent reduction in the direct combustion of coal in households, combined with a 16 percent decrease in the use of LPG. The remainder of cooking energy demand is consistent with the values projected by Mainali et al. (2012).

Improved Biomass and Electricity (China Cooking Fuel Mix Scenario 4)

The baseline 2030 BAU scenario values are adjusted in this scenario to explore the effect of policy support for advanced biomass stove use, combined with a 25 percent reduction in LPG use in favor of electricity. The 2030 BAU scenario shows a two-thirds reduction in the use of fuelwood and crop residue by the year 2030. This scenario supposes that a combination of factors works to hold the contribution of firewood and crop residues within the cooking fuel mix to a constant level. A recent survey conducted by The World Bank (2013) indicates that the production of advanced biomass stoves has increased rapidly since 2005. The increased thermal efficiency of these stoves allows the same delivery of heating energy, while decreasing the required demand for biomass. Biogas use is scaled up to utilize two-thirds of the national biogas potential, which is estimated to be approximately nine percent of cooking energy (World Bank 2013). The scenario also assumes that one quarter of the increase in modern fuel use, as it is modeled in the 2030 BAU scenario, accrues to electricity instead of LPG. Like the Increased Electricity scenario above, this shift would allow China to continue leveraging their significant domestic coal resources while reducing in-household exposure to HAPs. Combined, these shifts facilitate nearly a two-thirds reduction in reliance on solid coal combustion in the household.

Diverse Modern Fuels (China Cooking Fuel Mix Scenario 5)

The Diverse Modern Fuels scenario assumes that a balanced mix of modern fuels and advanced biomass options are adopted instead of coal, dung, and firewood combustion. The scenario assumes a 75 percent reduction in coal use, which leaves six percent of households still reliant on this fuel source. A five percent increase in the use of electricity is assumed over the projected ten percent contribution from the BAU 2030 scenario. It is assumed that 100 percent of biomass fuel consumption projected by the BAU 2030 scenario is consumed in advanced pellet stoves. Four percent of households cook with biogas, and the remainder of cooking energy is provided by modern liquid and gas options that tend to be favored as household incomes increase (Malla and Timilsina 2014). Reliance on coal gas is assumed to be limited to just three percent of cooking energy. Unlike the BAU projections, this scenario assumes a large increase in natural gas use, which offsets a portion of LPG production. This switch is supported by IEA projections that show both domestic production and imports of natural gas increasing significantly between now and 2030 (IEA 2007). The ratio of LPG to natural gas adoption is assumed to be three-to-one. Together, these two fuels account for 61 percent of cooking energy.

3.1.3 Kenya Cooking Fuel Mix Scenarios

Table 3-9 provides a name and basic description for each of the five fuel mix scenarios for Kenya. Table 3-10 introduces the cooking fuels that comprise each scenario and compares those values to the current cooking fuel mix. A full description of each scenario is provided in the subsections that follow. Details regarding fuel mix development and documentation are available in SI3.

Table 3-9. Cooking Fuel Mix Scenario Names and Descriptions for Kenya

Scenario	Scenario Name	Scenario Description
(1)	Current	Current fuel mix, recent year
(2)	BAU 2030	Applies current trends to the 2030 urban/rural population
(3)	Ghana Transition (for Kenya)	Models future cooking fuel mix shifts in Kenya based on Ghana’s fuel mix development since the mid-1990s when biomass and LPG use rates were like those found in Kenya today

Table 3-9. Cooking Fuel Mix Scenario Names and Descriptions for Kenya

Scenario	Scenario Name	Scenario Description
(4)	Slow Transition	Based on a slower transition to modern fuels and improved cookstoves than is in indicated by the Ghana Transition (for Kenya) scenario
(5)	Diverse Modern Fuels	Promotes a balanced use of modern fuels and improved stove technologies

Table 3-10. Cooking Fuel Mix Scenarios Evaluated for Kenya

Fuel Type	Current (1)[1]	BAU 2030 (2)[2]	Ghana Transition (for Kenya) (3)[2]	Slow Transition (4)[2]	Diverse Modern Fuels (5)[2]
Firewood	65%	68%	46%	56%	11%
Charcoal	17%	16%	27%	21%	17%
Kerosene	12%	10%	1.3%	6.2%	1.3%
LPG	5.0%	4.4%	24%	14%	36%
Electricity	0.80%	0.70%	1.0%	1.0%	13%
Biogas	0.70%	0.70%	1.0%	1.0%	3.0%
Biomass Pellets	-	-	-	-	19%
TOTAL[3]	*100%*	*100%*	*100%*	*100%*	*100%*

Sources: [1] KNBS 2012, [2] GVEP 2012a, CBS 2002
[3] Columns may not total 100 due to rounding, unrounded numbers available in SI

3.1.3.1 Current Baseline Scenario (*Kenya Cooking Fuel Mix Scenario 1*)

Firewood is the predominant cooking fuel used in Kenya today, providing nearly 65 percent of national cooking energy. Charcoal, another wood-based fuel, provides a further 17 percent of cooking energy. The two main references for the current cooking fuel mix disagree regarding current reliance on kerosene use with estimates of both five and 12 percent (KNBS 2012, Dalberg 2013a). Both fuel mixes refer to the data year 2009, with the national statistics being the preferred source for this phase of work. Use of the 12 percent kerosene estimate establishes a conservative baseline, and the discrepancy signals that Kenya may be in the process of accelerating adoption of modern fuels such as LPG. Electricity and biogas provide 0.8 and 0.7 percent of cooking energy, primarily in urban areas.

3.1.3.2 Potential Future Scenarios

BAU 2030 (Kenya Cooking Fuel Mix Scenario 2)

The BAU 2030 scenario is included to provide a conservative estimate of future cooking energy needs. The scenario applies current urban and rural cooking fuel use patterns to the projected urban and rural populations in the year 2030 in the absence of other pressures on the cooking fuel mix, as documented in SI3. The shifts in fuel mix do not exceed a few percentage points for any given fuel.

Ghana Transition (Kenya Cooking Fuel Mix Scenario 3)

The cooking fuel mix for this scenario is created using the recent experiences of Ghana in combination with Kenya's own data characterizing the early stages of a shift towards LPG and charcoal use. Charcoal use has been slowly rising in Kenya since the late 1980s when this fuel provided approximately seven percent of cooking energy (CBS 2002). Projecting forward along the same linear trend line, this scenario estimates that charcoal use could contribute 27 percent of cooking energy by the year 2030. This is the same level of market penetration that Ghana reached in the late 1980s and 1990s (GLSS2 2008, GLSS3 1995). LPG use in Kenya has risen rapidly from very low usage to comprise approximately five percent of the Kenyan cooking fuel mix (2010). A similar transition was observed in Ghana between the late 1980s and the turn of the 21^{st} century. Modeling Kenya based on the experience of Ghana following that period, the use of LPG can be expected to rise to nearly 25 percent of the overall cooking fuel mix. The use of kerosene is assumed to decline to five percent of the national cooking fuel mix. The remainder of the previously mentioned increases in fuel consumption are offset by decreased reliance on firewood, whose use is projected to fall to 46 percent of the cooking fuel mix by the year 2030. This trend is consistent with Ghana's experience, where gains in LPG and charcoal contributed to a decrease in demand for firewood.

Slow Transition (Kenya Cooking Fuel Mix Scenario 4)

The stability of Kenya's cooking energy mix and their slower pace of urbanization over the past three decades is an indicator that Kenya may move more slowly away from firewood than Ghana's experience suggests. The Slow Transition scenario uses the same approach as that developed in the previously described Ghana Transition (for Kenya) scenario, but the rate of conversion to charcoal and LPG use is cut in half. In this scenario, kerosene use declines more slowly to provide six percent of the cooking fuel mix, consistent with the slow decline in kerosene use that Kenya has experienced thus far. Still, LPG use triples its contribution to the cooking fuel mix, rising to provide 14 percent of total cooking energy. Charcoal use increases by 25 percent to provide 21 percent of cooking energy. It is assumed that the marginally used alternative fuels, electricity and biogas, see an increase in use but remain as minor contributors to the total fuel mix. To compensate for increased use of charcoal and modern fuels, the use of firewood decreases by 14 percent to contribute approximately 56 percent of the national cooking fuel.

Diverse Modern Fuels (Kenya Cooking Fuel Mix Scenario 5)

The Diverse Modern Fuels scenario is designed to explore the potential benefits and burdens of a more rapid shift to a diverse portfolio of modern cooking fuels and improved stove designs. Use of LPG, electricity, and biomass pellets are all assumed to rise significantly in this scenario. African nations such as South Africa and Zimbabwe, which, respectively, generate 85 and 73 percent of urban cooking energy from electricity, indicate that widespread adoption of electricity as a cooking energy is possible. However, it would take time to reach this level of market penetration, so this scenario assumes that 30 percent of urban cooking energy is provided by electricity. Electricity use is assumed to expand much more modestly in rural areas, eventually comprising five percent of the rural cooking fuel mix. LPG use rises to provide approximately 36 percent of national cooking energy, while reliance on kerosene falls to just 1.3 percent. Charcoal use remains nearly constant with its observed level of use in the current cooking fuel mix. Charcoal use is assumed to continue expanding in rural areas to satisfy 22 percent of total rural cooking energy, while its use falls in urban areas in favor of other modern fuels. All firewood is assumed to be eliminated from use in urban areas with a fraction of that demand being replaced by the use of biomass pellets. The use of biomass-based fuels decreases only modestly in rural areas, but the adoption of wood pellet stoves increases dramatically to provide 22 percent of rural cooking energy. This shift increases the efficiency of biomass utilization while simultaneously providing a rural employment opportunity for those workers who used to satisfy the urban charcoal market.

3.1.4 Ghana Cooking Fuel Mix Scenarios

Table 3-11 provides a name and basic description for each of the four fuel mix scenarios for Ghana. Table 3-12 introduces the cooking fuels that contribute to each scenario and compares those values to the current cooking fuel mix. A full description of each scenario is provided in the subsections that follow. Details regarding fuel mix development and documentation are available in SI3.

Table 3-11. Cooking Fuel Mix Scenario Names and Descriptions for Ghana

Scenario	Scenario Name	Scenario Description
(1)	Current	Current fuel mix, recent year
(2)	BAU 2030	Applies current trends to the 2030 urban/rural population
(3)	Moderated Growth	Reflects a slowdown in the current growth of LPG
(4)	Fast Growth	Based on a continued rapid growth in LPG use
(5)	Diverse Modern Fuels	Promotes a balanced use of modern fuels and improved stove technologies

Table 3-12. Cooking Fuel Mix Scenarios Evaluated for Ghana

	Current (1)	BAU 2030 (2)	Moderated Growth (3)	Fast Growth (4)	Diverse Modern Fuels (5)
Biomass	46%	39%	26%	14%	16%
Firewood	46%	38%	26%	14%	16%
Crop Residue	0.41%	0.30%	0.37%	0.26%	-
Charcoal	32%	35%	32%	23%	20%
Kerosene	0.2%	-	-	-	-
LPG	22%	26%	40%	61%	30%
Electricity	0.32%	-	1.9%	1.9%	21%
Biomass Pellets	-	-	-	-	13%
Total[1]	100%		100%	100%	100%

Sources: All scenarios based on GLSS1 through GLSS6, GSS 2012, and Dalberg 2013a
[1] Columns may not total 100 due to rounding, unrounded numbers available in SI

3.1.4.1 Current Baseline Scenario (Ghana Cooking Fuel Mix Scenario 1)

The current cooking fuel mix in Ghana relies on unprocessed firewood for 43 percent of cooking energy, charcoal for 33 percent, and LPG for 23 percent. LPG is primarily used in urban areas (GLSS6 2014). Electricity, kerosene, and crop residues contribute the remaining one percent of cooking energy.

3.1.4.2 Potential Future Scenarios

BAU 2030 (Ghana Cooking Fuel Mix Scenario 2)

The BAU 2030 scenario is included to provide a conservative estimate of future cooking energy needs. The scenario applies current urban and rural cooking fuel use patterns to projected urban and rural populations in the year 2030 in the absence of other pressures on the cooking fuel mix, as documented in SI3. Reliance on traditional biomass falls to provide approximately 39 percent of cooking energy, while charcoal use increases to 35 percent. LPG use also increases a few percentage points to provide nearly 26 percent of cooking energy.

Moderated Growth (Ghana Cooking Fuel Mix Scenario 2)

The Moderated Growth scenario assumes that the use of firewood continues to fall at a rate just below that observed over the period from 1980 to the present. This scenario predicts that the contribution of firewood to the cooking energy mix drops to just over 25 percent by the year 2030. In this scenario, charcoal use is predicted to continue its pattern of flat growth over the same period. LPG use is expected to continue to rise as it has in the recent past, but the pace of growth slows down. In the Moderated Growth scenario LPG is assumed to provide 40 percent of cooking energy. There are several reasons supporting the possibility of such a scenario. The literature recognizes a complex set of factors, which contribute to a household’s selection of cooking fuel (Malla and Timilsina 2014). The realities of cost, taste preference, and fuel availability are but a few of the many factors that could challenge the current rapid growth in LPG fuel use. In particular, Ghana has a long history of cooking over firewood and charcoal, both of which lend a desirable flavor to many traditional dishes. As the experience of other countries has shown, the complete elimination of traditional fuels can be a long process. On top of this, it is important to consider the stated goals of Ghana’s government and other organizations to enhance access to improved cookstoves and efficient kiln technology (GEC 2006).

Fast Growth (Ghana Cooking Fuel Mix Scenario 3)

Since 1987, the share of LPG in the national fuel mix has risen from 0.8 to 22 percent. Charcoal use has increased at a more moderate pace rising from 26 to 31 percent by the year 2000 and has remained relatively flat since that time. All the while, the use of unprocessed firewood has continued its steady decline from 70 to 40 percent of the national cooking fuel mix. If these trends were to continue unabated, the use of LPG could provide over 60 percent of cooking energy by the year 2030. For this to occur, the decrease in reliance on solid wood fuel would have to quicken slightly. In this scenario, it is assumed that the use of wood in urban areas drops to zero from its current level of approximately 14 percent. Rural wood use would need to drop far more dramatically, from 75 to 14 percent. This scenario also assumes that charcoal use in urban areas is reduced in favor of LPG, while it holds roughly constant in rural regions. There is evidence that charcoal is being displaced by LPG in urban areas. Between the 5th and 6th Ghana Living Standards Surveys, reliance on charcoal in urban areas dropped by nearly 20 percent with LPG absorbing much of that energy demand. Both Ghana’s government and international organizations are supporting the shift to modern fuels, and intervention from these actors is likely to be required if such a scenario is to be realized.

Diverse Modern Fuels (Ghana Cooking Fuel Mix Scenario 4)

The Diverse Modern Fuels scenario is designed to explore the potential benefits and burdens of a more rapid shift to a diverse portfolio of modern cooking fuels and improved stove designs. LPG use is projected to grow to comprise 30 percent of the cooking fuel mix, which represents a moderated rate of LPG growth in favor of other modern fuels. Reliance on wood resources falls to below 30 percent of cooking fuel energy, and 45 percent is assumed to be consumed in improved biomass pellet stoves. Charcoal use is assumed to drop, providing approximately 20 percent of cooking energy in the year 2030. Use of electricity as a cooking fuel rises dramatically to comprise 20 percent of the cooking fuel mix, as it offsets charcoal and LPG use.

3.2 Electrical Grid Scenario Development

The fuel mix that underlies the electricity grid is a key factor in the environmental impact of electric powered cookstoves and upstream manufacturing associated with cooking fuels that require industrial processing. As a sensitivity analysis within this study, a range of projected grid mixes for India, China, Kenya, and Ghana have been included, following a review of the available literature. Important factors that influence the adoption of specific fuels include population and economic growth, changes in the relative cost between fuels and generation technologies, and national and international government policies concerning environmental management and the trade of goods. Scenarios included in the sensitivity analysis range from those based on a moderate BAU perspective to scenarios that embrace climate change mitigation and dramatically pursue electricity production based upon renewable fuels.

It is not just electricity fuel mix that is expected to change in the coming decades. Dramatic shifts in generation technology promise to wring more kilowatt hours out of each unit of fuel burned. In particular, the pursuit of advanced coal burning technologies such as supercritical, ultra-supercritical, and IGCC generators could have a dramatic effect on emissions even if the proportion of the grid fueled by coal remains high. The possibility of carbon capture and storage (CCS) also provides an attractive option for countries that have ample coal resources and well established production chains for these commodities. The possibility of adopting advanced generation technologies is also considered in these scenarios.

A standard generating technology has been assumed for each fuel that is consistent with those used in the first phase of this study. For example, the vast majority of coal-based power plants in India and China today rely on subcritical generation technology. The following list describes adaptations made to base coal and natural gas generation technologies to reflect advancements expected to figure prominently into the electricity scenarios over the next ten to 30 years. Documentation of emission adjustments incorporated in the LCI for each electricity generation unit process are included in SI4.

Natural Gas - Efficient

A number of the scenarios generated by The Energy and Resources Institute (TERI) in India predict the uptake of advanced gas combustion technologies. Natural gas combined cycle (NGCC) is one example of such advancements. As foreseen by TERI (2006), the efficient natural gas unit process is modeled as having a 39.4 percent generator efficiency as compared to current natural gas generator efficiency of 34.5 percent.

Natural Gas + CCS

Natural Gas with CCS is modeled as being based on generation technology with a thermal efficiency of 39.4 percent. Due to the energy penalty of CCS, the effective thermal efficiency is reduced to 33.5 percent., which constitutes an approximate 15 percent increase in fuel demand per delivered kWh. The CCS system is assumed to capture 90 percent of CO_2 emissions, while NOx emissions increase by a factor of 1.15. Total life cycle carbon emissions are reduced by 79 percent per unit of delivered energy (Odeh and Cockerill 2008).

Coal Supercritical

Supercritical coal power plant technology has an associated thermal efficiency of 39.6 percent. This increase in efficiency drives a 10.6 percent reduction in life cycle CO_2 emissions relative to subcritical generation. Increased combustion efficiency also decreases emission of NOx, SOx, and PM by 84, 88, and 88 percent, respectively, relative to subcritical reactors (Odeh and Cockerill 2008).

Coal Ultra-Supercritical

Ultra-supercritical generation is modeled as having a thermal efficiency of 43 percent, which yields a 13 percent reduction in life cycle CO_2 emissions. Due to a lack of data, the emission reductions for NOx, SOx, and PM are modeled as being the same as those associated with the supercritical reactor.

Coal IGCC

Power plants using IGCC technology use a combination of gas and steam turbines to achieve higher electrical efficiency per unit of fuel. This increased efficiency leads to a reduction in GHG emissions as a result of burning less fuel. The thermal efficiency of an IGCC reactor is assumed to be 37.2 percent. The combustion process is also more efficient and reductions of 96, 96, and 99 percent are achieved, as compared to conventional technology, for SOx, NOx, and PM, respectively (Odeh and Cockerill 2008, Beer 2005).

Coal + CCS

CCS technology is assumed to be paired with supercritical generating facilities. The addition of CCS facilities and additional emission control features, necessary to control SOx for the benefit of efficient CCS, yields an effective reduction in thermal efficiency. Therefore, more fuel must be burned per kWh of electricity produced, but emissions per unit fuel combustion are dramatically reduced CCS facilities are assumed to be able to sequester 90 percent of combustion-related CO_2 emissions. SOx and PM emissions are reduced to just 0.12 percent and six percent of those associated with subcritical coal generation technology. NOx emissions are also reduced compared to conventional technology without CCS, but they increase slightly relative to the supercritical reactor without CCS.

The following subsections describe the projected electrical grid mixes for each nation studied that are considered in this report.

3.2.1 India Electrical Grid Scenarios

Figure 3-1 shows nine potential future Indian electrical grid mixes and compares them to the most recent IEA estimate of the Indian electrical grid mix for 2013 (IEA 2013a). Projections for the years 2021-2050 have been made by TERI, the U.S. Energy Information Administration (EIA), the IEA, and researchers at Imperial College in London. Scenarios for the year 2021 and more conservative fuel mix shifts are grouped to the left of the figure with those for later years and those encompassing more dramatic changes to the structure of the underlying fuel mix being grouped to the right. Generation technologies considered in this study are also depicted by changing the pattern of the bar while keeping the color constant, which allows readers to see both shifts in the fuel mix and the generation technology used.

Seventy-three percent of the current Indian electrical grid is fueled by the burning of coal in subcritical generators. Hydropower and natural gas provide a further 12 and five percent of electricity, respectively. Oil/diesel, nuclear and renewables each provide between two and three percent of electricity (IEA 2013a).

TERI is an Indian research group that has produced five projections for the electricity fuel mix between 2021 and 2031. The TERI scenarios are based on generating capacity, so load factors taken from the IEA for India were used to estimate electricity production from each source. All TERI scenarios foresee continued reliance on coal-based electricity over the next 15 years. Their 2021 BAU scenario projects that the coal share of the fuel mix drops to just over 50 percent, with the difference being made up by hydro, natural gas, and nuclear. In this scenario, hydropower provides 22 percent of all electricity, natural gas 16 percent, and reliance on nuclear doubles to provide nearly seven percent of electricity. Limited adoption of supercritical generator technology is anticipated. If India continues along this track, the share of coal in the electricity fuel mix is again expected to rise to almost 70 percent by the year 2031 to satisfy a nearly twofold increase in national energy demand. Use of renewables such as wind and biomass are expected to drop from their current level of three percent to provide less than 0.5 percent of electricity by 2031. Reliance on hydropower, natural gas, and nuclear all rise slightly in the 2031 BAU scenario (TERI 2006).

TERI's hybrid and efficiency scenarios for the year 2021 project a more rapid adoption of advanced coal generation technology, with their models showing a preference for IGCC generators. The use of nuclear increases to provide nearly 15 percent of electricity in the hybrid scenario, while hydropower supplies approximately 25 percent of electricity in both scenarios. The efficiency scenario projects lower adoption of nuclear and continues to rely on coal for 49 percent of electricity. Over two-thirds of coal electricity is generated by the more efficient IGCC power plants. The use of natural gas also increases in both the hybrid and efficient scenarios to comprise between 15 and 16 percent of the fuel mix. The 2031 TERI Efficiency scenario also projects that reliance on coal will pick up between the years 2021 and 2031 to meet a rapidly increasing demand for electricity. While coal is projected to provide just under 65 percent of electricity in 2031, over 60 percent of that electricity comes from more efficient IGCC power plants. Reliance on hydropower, natural gas, nuclear, and renewables shows a relative decrease as compared to the efficient 2021 scenario (TERI 2006).

The EIA 2030 scenario is similar in its predicted changes to what is observed in the TERI BAU scenario for 2021. Reliance on subcritical coal power plants contracts to provide 58 percent of electricity in 2030. Nuclear and natural gas use expand to provide over 11 and eight percent of electricity, respectively. Reliance on hydropower and alternative renewables does not change significantly from the hydropower and alternative renewables currently in use. The IEA 2050 scenario is similarly conservative with the use of coal expected to persist at a level near 70 percent. Hydropower is displaced partially by natural gas in the IEA 2050 scenario (IEA 2010).

Both the Low Carbon and Blue Map 2050 scenarios represent more radical departures from the current state of electrical generation in India. Both predict a widespread embrace of wind and solar technology. The Low Carbon scenario indicates that fully 42 percent of India’s electricity could be provided by solar energy in the year 2050 (Gambhir et al. 2012). The use of coal disappears completely in this scenario while use of nuclear, natural gas, and wind energy all rise. The IEA Blue Map scenario projects that 18 percent of electricity will still be generated using coal, but the majority of this 18 percent is subject to CCS. The use of nuclear rises to provide over 26 percent of electricity. Natural gas use rises to provide 16 percent of electricity with the adoption of more efficient turbines for two-thirds of this generating capacity (IEA 2010). Hydropower still provides approximately ten percent of electricity in both grids.

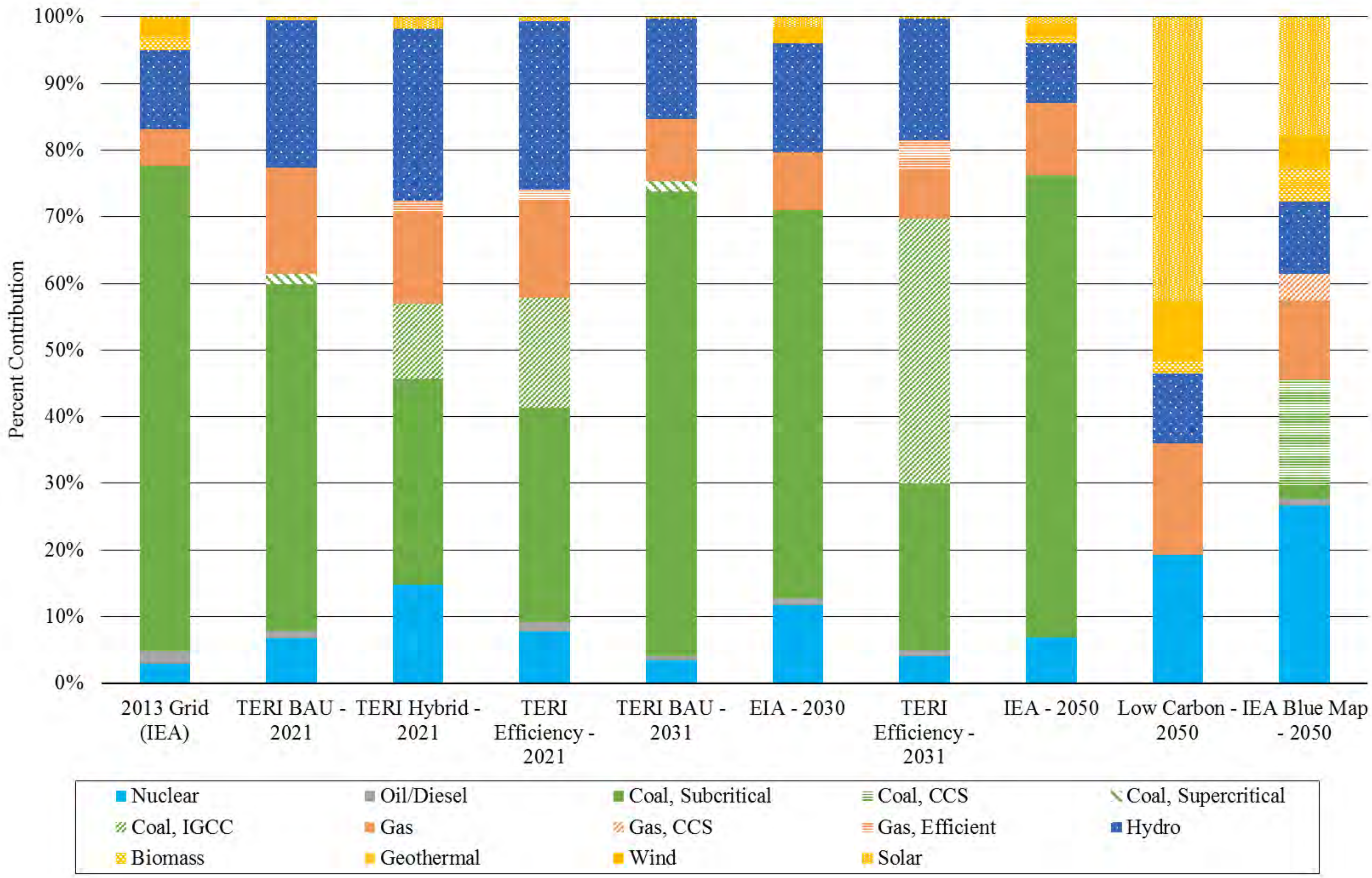


Figure 3-1. Potential future electrical grid mixes in India.

3.2.2 China Electrical Grid Scenarios

The future of the Chinese electricity sector is of great interest to the international community and has been reported extensively. Ten potential future grid mixes were found in the literature as reported by the IEA, the U.S. EIA, Lawrence Berkeley National Laboratory (LBNL), and the Boston Consulting Group (BCG). Figure 3-2 depicts these potential future Chinese grid mixes and compares them to the most recent IEA estimate of the Chinese electrical grid mix for 2013 (IEA 2013b). Scenarios for the year 2030 and more conservative fuel mix shifts are grouped to the left of the figure, while those for the year 2050 with more dramatic changes to the structure of the underlying fuel mix grouped to the right. Generation technologies considered in this study are also depicted by changing the pattern of the bar while keeping the color constant, which allows us to see both shifts in the fuel mix and the generation technology used.

Currently, over 75 percent of Chinese electricity is produced using coal energy. Hydropower is the next largest contributor providing almost 17 percent of electrical energy. Renewables, natural gas, and nuclear each provide between 1.5 and three percent to round out the rest of the grid.

The baseline and slow-shift BCG scenarios, the EIA 2030 and the IEA 2050 scenarios are conservative in the sense that they do not predict dramatic departures from the current structure of the Chinese grid. This is particularly true of the IEA 2050 scenario, given the longer timeframe available to affect a shift. Use of natural gas, nuclear, and renewables all expand in these four scenarios, but reliance on subcritical coal generation remains high, between 60 and 70 percent. Reliance on hydropower contracts slightly in these four scenarios, dropping from 15 percent in the current scenario to between six and 12 percent.

The LBNL Continued Improvement Scenario (CIS) 2030 scenario is interesting in that, while the underlying fuel mix remains similar to the current scenario in China, we see a near complete departure from subcritical generation technology towards supercritical and ultra-supercritical generators. Combined use of renewables such as solar, wind, and biomass triples, while the use of nuclear reactors expands six-fold to provide 13 percent of the electricity demand. The LBNL Accelerated Improvement Scenario (AIS) anticipates a similar shift in generation technology but combines that shift with a more rapid replacement of coal-fired generation with alternative options. Under the AIS scenario renewables, natural gas, hydropower, and nuclear expand to provide 12, 4, 17, and 19 percent of electricity, respectively (Zhou et al. 2011).

The BCG Clean 2030 scenario anticipates that subcritical coal technology still provides over 50 percent of China's electricity. Use of renewables expands to nearly 11 percent with over three quarters of that electricity produced by wind. In this scenario, use of nuclear and natural gas rises 13 and 15 percent, respectively. Reliance on hydropower falls by nearly half (Michael et al. 2013).

The LBNL CIS 2050 scenario anticipates that 47 percent of electricity is generated by coal with the major portion of that electricity generation occurring in ultra-supercritical generators. Use of nuclear is projected to rise to 24 percent. Reliance on natural gas remains relatively flat over time providing just under two percent of China's electricity. Reliance on hydropower falls only slightly to between 11 and 12 percent. Other renewables, particularly wind, constitute 14 percent of the fuel mix.

Both the LBNL AIS and IEA Blue Map scenarios are dramatic in their departure from the status quo, although they follow two distinct pathways. The LBNL AIS scenario predicts the adoption of nuclear technology throughout China, with over 50 percent of all electricity being produced from this fuel in the year 2050. Reliance on coal is projected to drop to less than ten percent of the total fuel mix. Renewables expand to provide 20 percent of all electricity, while reliance on hydropower remains roughly constant with 16 percent of electricity being provided by this source in the year 2050. The IEA Blue Map scenario also sees the use of nuclear power increase, but more modestly, to the point that nuclear power provides 25 percent of electricity in the year 2050. Use of coal drops to 15 percent and the major portion of that coal-generated electricity is paired with CCS technology. Use of alternative renewables such as wind and solar is projected to rise to provide 22 percent of all electricity. In this scenario, the use of natural gas expands significantly to provide 23 percent of electrical energy (IEA 2010).

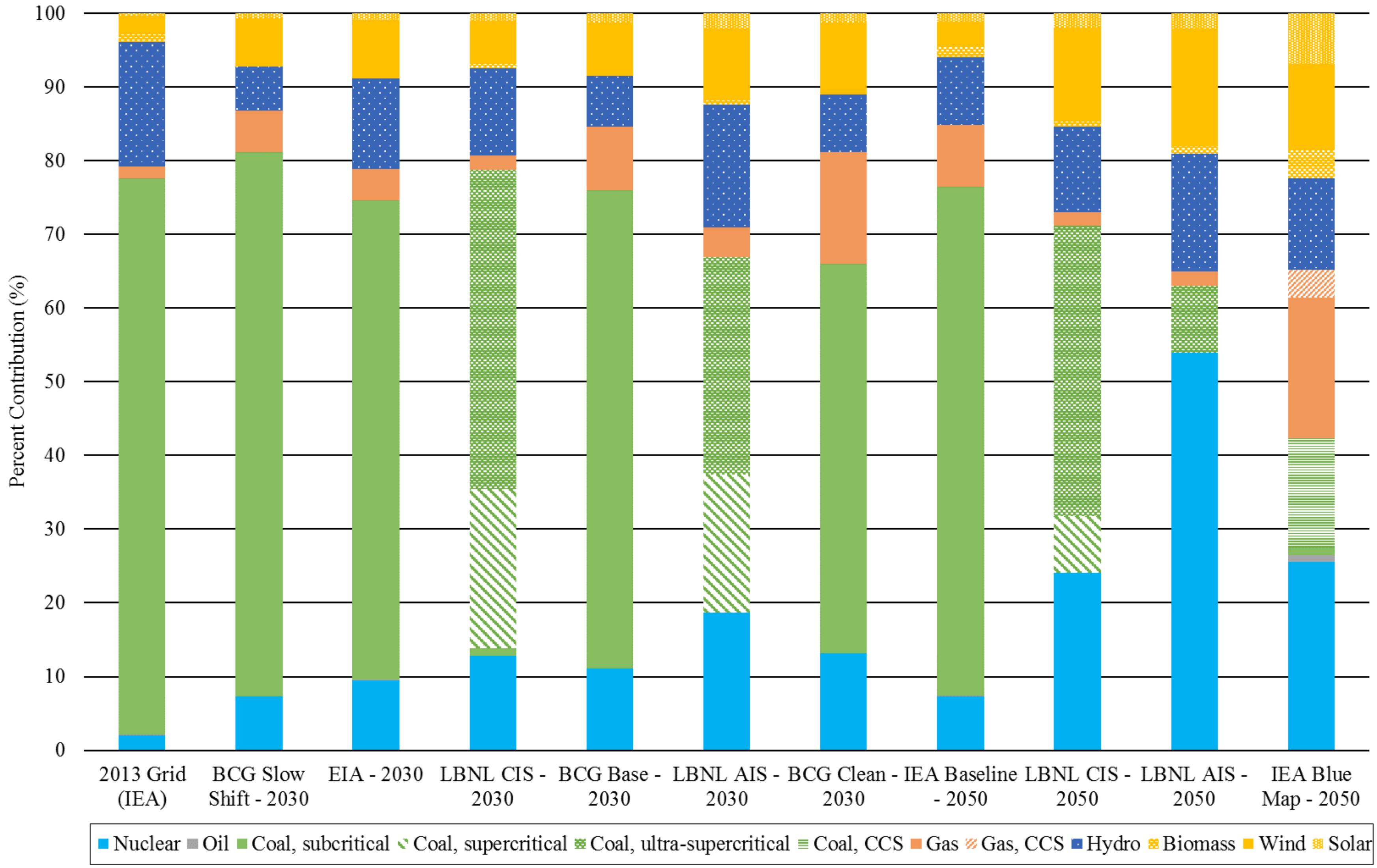


Figure 3-2. Potential future electrical grid mixes in China.

3.2.3 Kenya Electrical Grid Scenarios

Currently, 23 percent of Kenyan households are connected to the electrical grid, while less than one percent of households utilize electricity as their primary cooking fuel (World Bank 2012). Electricity access is concentrated in urban areas. There is a massive potential for increased electricity demand, and with so much new generating capacity being built, the possibility of shifting towards a dramatically different fuel mix is quite high. In Kenya, total installed capacity is expected to increase from 1.3 GW in 2011 to between 17 and 30 GW in the year 2031, a potential 23-fold increase (ROK 2011). Figure 3-3 depicts five potential future Kenyan grid mixes and compares them to the most recent IEA estimate of the Kenyan electrical grid mix for 2013 (IEA 2013c). Scenarios for the year 2030 are grouped to the left of the figure, while those for the year 2040 are grouped to the right.

The current Kenyan grid is fueled by hydropower, fuel oil, and geothermal energy, with each, respectively, providing 44, 31, and 23 percent of electricity. Biofuels provide the remaining two percent.

The three 2031 scenarios were developed by the Kenyan government using a least cost approach that adds generating capacity as is required to minimize the long run marginal cost of electricity. The Kenyan government’s model selects the least cost option from among a list of project plans subject to a number of constraints such as the maximum number of a given plant type that could feasibly be built annually. The base case (Least Cost – 2031) respects their full list of constraints and is required to supply 18.9 additional GW of generating capacity by the year 2031. The results of this model run indicate that reliance on geothermal energy increases by nearly a third, the use of oil declines by nearly two-thirds, and the contribution from hydroelectricity drops over tenfold. Wind, coal, natural gas, and nuclear technology increase from current marginal levels to satisfy the remaining demand. Nuclear capacity increases the most dramatically to supply 30 percent of electrical energy in the year 2031 (ROK 2011).

Republic of Kenya’s (ROK’s) low and high demand scenarios were developed using the same least cost approach and vary only in the amount of generating capacity that must be provided. The low demand scenario realizes slightly lower deployment of wind, hydropower, and coal technology than does the base case, while the use of nuclear and geothermal satisfy a larger portion of electricity demand. The high demand scenario relies heavily on nuclear technology, which provides 49 percent of electrical energy in the year 2030. The contribution of wind and geothermal energy are lower relative to the other scenarios developed by the Kenyan government with these options providing eight and 22 percent of electricity, respectively. All three scenarios are dramatically different from the 2013 grid mix with significant decreases in reliance on oil and hydropower.

The McKinsey & Company 2040 scenario decides to avoid nuclear as a potential source of electrical energy, based on their judgment that this option is not feasible in Sub-Saharan Africa due to high up-front costs, potential community opposition, and lack of local trained professionals in that sector (Castellano et al. 2015). The Kenyan government’s least cost model excluded solar as an option. By 2040, the McKinsey model foresees oil fueling only four percent of Kenya’s electricity production, down from 25 percent today. They too project a rapid decrease in reliance on hydropower, but the drop is less dramatic, with 30 percent of electricity still being provided by this source in the year 2040. Reliance on geothermal also falls, to provide only nine percent of electrical energy. McKinsey expects the costs of solar to be much more competitive by the year 2040, which facilitates its rising contribution to the grid mix. Use of natural gas rises dramatically from zero today to provide almost half of Kenya's electricity in 2040 (Castellano et al. 2015).

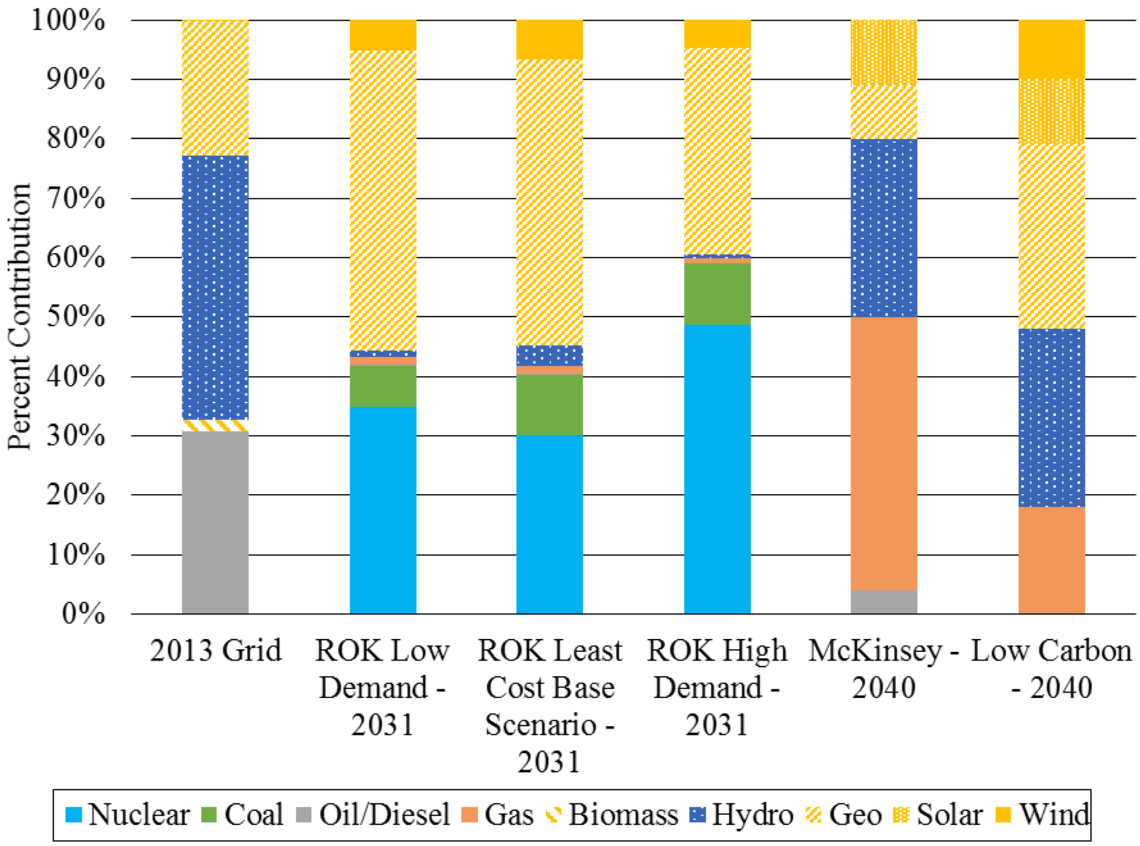


Figure 3-3. Potential future electrical grid mixes in Kenya.

The Low Carbon scenario was developed for this project to provide a clean option comparable to the IEA Blue Map scenarios available for India and China. This scenario adheres to McKinsey's judgment that nuclear technology is an unlikely option in Sub-Saharan Africa (Castellano et al. 2015). This scenario selects the highest deployment of solar, wind, geothermal, and hydropower that are projected by the least cost models and satisfies the remaining 18 percent of electricity demand with natural gas.

3.2.4 Ghana Electrical Grid Scenarios

Ghana's electrification rate is approximately 64 percent, with over 85 percent of urban residents having access to electricity (World Bank 2012). Still, demand for electricity is projected to increase rapidly in the coming decades with a nearly threefold increase projected for the period between 2012 and 2020 (GEC 2006). Few projections of the future electricity fuel mix in Ghana were found in the literature. Ghana's energy commission projects that the 2020 electricity mix will fall somewhere within the ranges depicted in Table 3-13 (GEC 2006). These ranges have been used to create three scenarios in addition to a fourth low carbon-renewable scenario as shown in Figure 3-4.

Table 3-13. Projected Electrical Grid Mix Contributions by Fuel for Ghana 2020

Fuel Source	Grid Mix Contribution (%)
Hydropower	39-49
Thermal	41-51
Nuclear	3-8
Renewables	5-11

Source: GEC 2006

The current electrical grid mix is dominated by hydropower, which provides 64 percent of all electricity. Oil-powered generation supplies a further 26 percent of electrical energy, with the remaining ten percent being provided by natural gas.

Ghana's government projects that reliance on hydropower will drop from its current high level to provide between 39 and 49 percent of electricity in the year 2020. Thermal capacity will expand with a preference for natural gas and coal power plants as an option to replace Ghana's current reliance on fuel oil/diesel. Nuclear energy is projected to emerge in Ghana and to provide between three and eight percent of electricity. Other renewables are expected to expand to provide between five and 11 percent of electricity. These projections were initially made in the year 2006, and based on the 2013 grid, it appears that this transition is happening more slowly than expected, which likely pushes back the expected transition dates from 2020 to 2030 and beyond.

The thermal scenario represents the maximum projected reliance on thermal generating sources such as natural gas and coal and assumes that two-thirds of thermal power is fueled by natural gas. This scenario also assumes adoption of renewables on the lower end of the projected range, seven percent. No nuclear reactors are assumed to be built in this scenario.

The nuclear scenario assumes an eight percent reliance on nuclear energy for electricity production. All other fuel sources are increased proportionally to their minimum projected value in the grid mix. Natural gas is supposed to be the only source of fossil fuel-based thermal power and it supplies 44 percent of all electricity. Hydropower provides 42 percent of electricity while non-hydro renewables supply the remaining five percent of electricity demand.

The renewable scenario assumes that 49 percent of electricity is produced by hydropower, which is the highest level foreseen by Ghana's energy commission (GEC 2006). The lowest projected level of reliance on thermal generation is projected for this scenario, with 11 percent of electricity coming from non-hydro renewables.

As was done for Kenya, a Low Carbon scenario was included to represent a more dramatic departure from the current electricity grid mix in line with the IEA Blue Map scenarios for India and China. In this scenario, 26 percent of electricity is provided by non-hydro renewables. The international renewable energy agency (IRENA 2013) reports that Ghana has significant renewable energy resources, which are more than capable of satisfying Ghana's demand. Given the extended time horizon for this scenario, electricity demand is assumed to increase significantly. The share of hydropower drops to provide 35 percent of electricity under this scenario as the best dam locations become developed favoring other fuel options. Nuclear is assumed to provide 15 percent of Ghana's electricity, a rate that is twice the maximum contribution projected by the government for the year 2020. The remaining 15 percent of electricity demand is satisfied by natural gas. Half of gas production capacity is assumed to rely on efficient power plant technology.

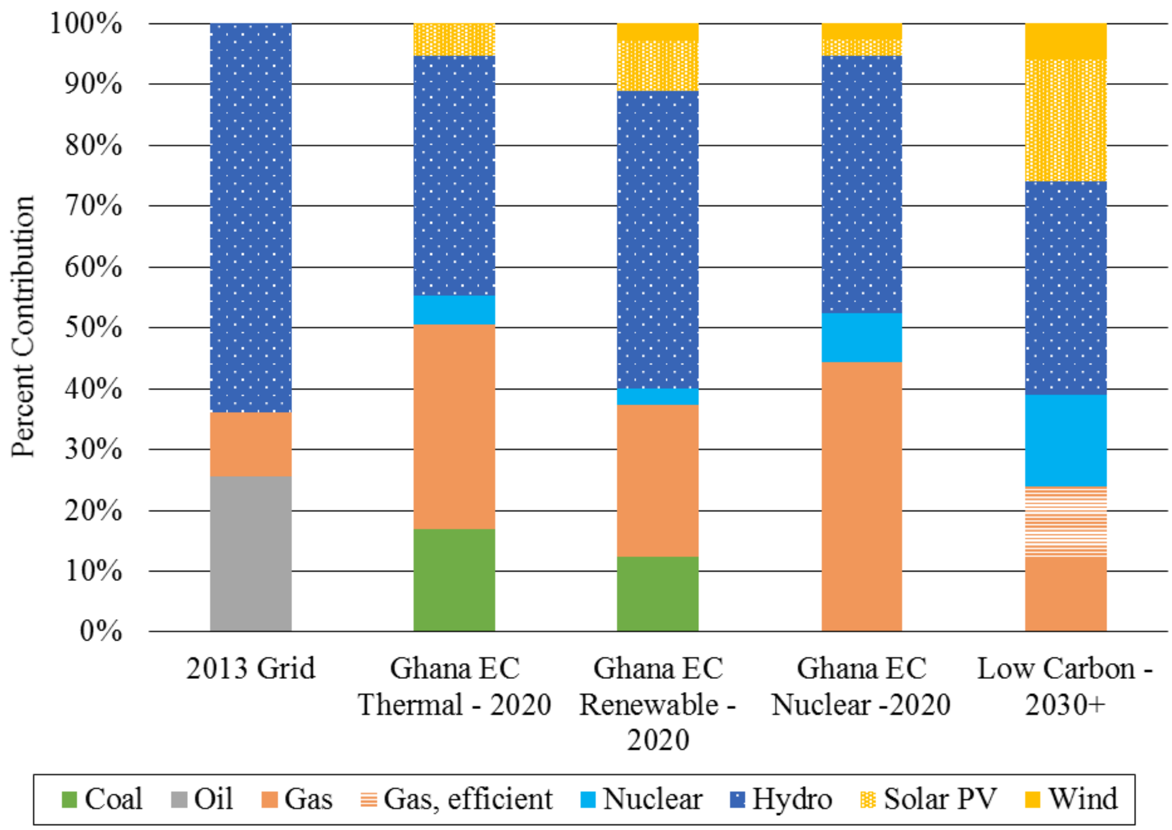


Figure 3-4. Potential future electrical grid mixes in Ghana.

3.3 <u>Allocation Approach</u>

Several cooking fuels examined such as crop residues, ethanol, and biogas are produced by multi-output processes. Allocation is required for partitioning burdens among the various co-products. Table 3-14 lists the baseline allocation approach and the allocation and modeling conventions employed in the sensitivity analysis.

Table 3-14. Summary of Baseline and Sensitivity LCA Modeling and Allocation Options

Fuel Type	Baseline Allocation Approach	Sensitivity Allocation Approach
Crop Residue	Cut-off	Physical Allocation
		Economic Allocation
		System Expansion
Sugarcane Ethanol	Physical Allocation	Economic Allocation
		System Expansion
Biogas	Cut-off	Economic Allocation
		System Expansion

ISO 14044 suggests that allocation be avoided either by using system expansion or by breaking up manufacturing into multiple unit processes. This scenario is not always possible, making allocation necessary. No single allocation approach is suitable for every scenario. The method used for handling product allocation varies from one system to another, but the choice of allocation is not arbitrary. ISO 14044, Section 4.3.4.2 states that "the inventory is based on material balances between input and output. Allocation procedures should therefore approximate as much as possible such fundamental input/output relationships and characteristics (ISO 2010b)." Under Phase I of this study, the baseline method used for modeling multi-output product processes with one primary product and one or more unavoidable co-products was the "cut-off" approach. Using this approach, all burdens are assigned to the primary product (Baumann and Tillman 2004).

Physical allocation is generally recommended within LCA studies due to its ease and reproducibility. However, physical relationships do not always lead to a fair allocation of environmental burdens between products and co-products. The allocation of impacts between food crops and co-produced crop residues is a classic example where physical allocation does not lead to allocation fractions that reflect the underlying drivers of environmental damage. The residue portion of the plant in many cases has mass equal or greater than the food crop itself.

Economic allocation is a third means of distributing environmental burden between products and co-products. This method assumes that economic demand is the driving factor behind supply-chain activities and their attendant environmental impacts. The relative economic value between products and co-products can be used to allocate environmental impact. This scheme is complicated by crop residues, for example, often considered to be free by farmers, which supports the previous use of the cut-off method. However, considering crop residues 'free' neglects their value as cooking fuels or the value of alternative uses such as for animal feed or soil fertilization and conditioning. Use of economic allocation requires the determination of a price for all allocated products and co-products, a process that can be difficult for goods such as crop residues and gathered firewood that often have no widely available market price. Market price may also fluctuate widely, while the physical properties of the biomass remain unchanged. A number of valuation strategies can be employed to set a price in the absence of market pricing.

- **Substitute Value:** Substitute use valuation assumes that the value of the good in question is equal to the value of an equivalent good for which a market price is available.

- **Alternative Use Value:** Alternative use valuation of a product assumes that the value of a product in one application is equivalent to a known value for that product in another application.

- **Labor Value:** Labor use valuation assumes that the value of a given non-market good is equal to the labor cost necessary to obtain that good.

In addition to both physical and economic allocation, and as recommended by ISO 14044, this study employs system expansion in the sensitivity analyses to avoid the allocation of environmental burdens between products and co-products. By expanding the system boundaries, both the environmental impacts of co-product production and the impacts and avoided impacts of co-product use are attributed to the main product. The net effect of this choice can be either positive or negative, with net positive effects leading to the attribution of environmental credits.

3.3.1 Allocation to Crop Residues

Both Phase I and II of this project employ the cut-off method as the baseline LCA modeling convention for crop residue production. The cut-off method considers crop residues as a necessary by-product of food crop production and thereby attributes to them none of the environmental impacts of agricultural processes.

The use of physical and economic allocation as well as system expansion is included in Phase II to explore both the magnitude of the potential contribution of agriculture to cooking impacts and alternate approaches to allocating environmental burdens between food crops and crop residues. The use of crop residues as a cooking fuel is not common in Kenya and Ghana, and this allocation sensitivity was not carried out for the African countries.

While a case can be made for allocating environmental burdens solely to foodstuffs, there is a rationale for considering crop residues and the goods and services that they produce to be valuable co-products. The sheer magnitude of these biological resources is difficult to ignore. In India and China combined, upwards of 1.5 billion metric tons of crop residue are estimated to be produced per annum (see Table 3-15). For centuries, this material has served as fodder for animals and as a valuable soil amendment. Likewise, we understand from our initial study both the importance and impact of these materials as cooking and home heating fuels. Increasingly, there are competing interests for these materials as bio-based feedstocks for paper, textiles, and chemicals, all of which serve as valid reasons to allocate a portion of the environmental footprint of agriculture for crop residues such as straw and corn stover.

Table 3-15. Crop-to-Residue Ratios, Production, and Fraction of Crop Residue Produced – India and China

Crop	Crop-to-Residue Ratio[1]	India 2012 Production (10,000 tons)[2]	India Fraction of total Crop Residue (%)[5]	China 2012 Production (10,000 tons)[2]	China Fraction of total Crop Residue (%)[5]
Wheat	1.00	9,490	15%	12,100	13%
Rice[3]	1.21	15,800	30%	20,400	25%
Corn	2.00	2,230	5%	20,600	43%
Sugarcane[4]	1.50	36,100	17%	12,300	4%
Beans	1.00	3,140	7%	1,300	2%
Tubers	3.00	5,130	8%	3,290	3%
Cotton	2.00	582	3%	684	2%
Oil Crops	0.240	4,020	13%	3,440	7%
Totals	-	76,500	-	74,100	-

Notes and Sources: [1] FAO 2012, [2] Zhenhong 2001, [3] includes both straw and husk, [4] sugarcane tops are the available residue, [5] column value may not add to totals due to rounding.

System Expansion

The system expansion approach considered in the sensitivity analysis is based on the assumption that a hierarchy of uses exists for crop residues that include use as animal fodder, soil conditioner, cooking fuel, and field burning. Field burning is assumed to be the least preferable use of crop residues, and occurs only in the absence of demand for higher uses. The burning of crop residue as a cooking fuel is assumed to replace field burning, which would be the alternative use of those crop residues if they were not utilized for cooking. In India and China, respectively, approximately 19 and eight percent of crop residues are being disposed of by way of burning on the field (FAOSTAT 2016). Field burning is considered a form of waste disposal. Because crop residues are not being fully utilized for beneficial purposes, any use of crop residues for cooking fuel can be assumed to avoid the necessity of crop burning, and can be credited with the environmental benefit of this avoided action (Weidema 2000).

Physical Allocation

Physical allocation is not generally used to allocate between food crops and their co-products, as physical relationships are generally not assumed to drive agricultural inputs, farming practices, and their attendant environmental benefits and impacts. Physical allocation is included in this project as part of the sensitivity analysis to develop the fullest possible understanding of the potential distribution of impacts between food crops and crop residues. That is, the physical allocation approach is likely to provide the upper bound of impact results for crop residues. The full range of reported crop-to-residue ratios are used in these calculations. The national average portion of residues re-incorporated into the soil or burned on the field is subtracted from crop residue production and is allocated no impacts. This choice is made to reflect the national average context within each nation studied.

Economic Allocation

All economic allocations are performed on values transformed to 2014 U.S. dollars. This study assumes that firewood is the fuel that crop residues would substitute for. Values associated with the firewood substitution are based on the market price of firewood in India. The cost of firewood is first converted to dollars/MJ-delivered and then this value is applied to crop residues, thereby accounting for the difference in energy content and stove combustion efficiency that exists between these feedstocks. The labor value is based on estimated levels of effort necessary to collect the substitute fuel, firewood. Differences in stove thermal efficiency and heat content of the two fuels are again corrected. For India, the value of labor is based on the current national minimum wage in India of 160 Rupees per day, which is approximately 0.32 dollars per hour assuming an eight-hour workday (Jadhav 2015). The alternative use allocation is based on the substitute value of crops for use as fertilizer. The value of various fertilizers in India has been determined on the basis of U.S. dollars per kg of nitrogen, phosphorus, and potassium (NPK). All nutrients are assumed to contribute equally to the value of a fertilizer. The equivalent nutrient content of each crop residue type is calculated, and the value per kg of NPK calculated for various fertilizers is applied to the residue to determine a range of estimated values realized by the farmer in reduced fertilization costs. Low and high estimates of crop residue value calculated using the above methods are used in combination with high and low estimates of crop residue production per kilogram of crop production, respectively, to capture the full potential range of allocation fractions. The average of all economic allocation values is considered in the sensitivity analysis. This same method of economic allocation was applied for the China scope.

Table 3-16 shows the allocation percentages determined for major biomass crops in India and China. The underlying data and calculations associated with both physical and economic allocation are documented in SI5.

Table 3-16. Crop Residue Allocation Factors - India and China

Allocation Approach[1]	India		China		India		China		India		China	
	Wheat	Wheat Straw	Wheat	Wheat Straw	Rice	Rice Straw	Rice	Rice Straw	Sugarcane	Sugarcane Tops	Maize	Maize Stover
Physical, residue low	59%	41%	61%	39%	69%	31%	72%	28%	93%	7%	49%	51%
Physical, residue average	47%	53%	50%	50%	53%	47%	56%	44%	88%	12%	44%	56%
Physical, residue high	33%	67%	41%	59%	45%	55%	47%	53%	83%	17%	-	-
Economic, coal substitution, residue low, low value	96%	4%	95%	5%	98%	2%	97%	3%	97%	3%	88%	12%
Economic, coal substitution, residue high, high value	73%	27%	87%	13%	87%	13%	90%	10%	92%	8%	84%	16%
Economic, labor value, residue low, low value	99%	1%	97%	3%	99%	1%	94%	6%	92%	8%	89%	11%
Economic, labor value, residue high, high value	90%	10%	92%	8%	95%	5%	98%	2%	99%	1%	93%	7%
Economic, alternative use, residue low, low value	99%	1%	98%	2%	100%	0%	99%	1%	100%	0%	96%	4%
Economic, alternative use, residue high, high value	93%	7%	95%	5%	95%	5%	94%	6%	98%	2%	94%	6%
Economic, average	92%	8%	94%	6%	96%	4%	95%	5%	96%	4%	91%	9%

[1] Allocation approach labels list the valuation method used, the estimate of crop residue production used (low/high), and where applicable whether the low, high or average valuation estimate is used to calculate the associated allocation factor.

3.3.1.1 Crop Residue LCI Modeling

The LCI of each crop aims to capture the national average agricultural production practices within each country. It is the environmental effect of this LCI that is being allocated between crops and crop residues in the sensitivity analysis. An uncertainty range has been developed for each input and output with the crop LCIs, which is meant to capture the breadth of climatic and cultural practices affecting these values within each study country.

Yield per hectare is perhaps the dominant determinant of emissions per kg of crop output, which is the basis of this LCI. This determinant is true both for a specific crop and also between crop types. The large sugarcane biomass yields per hectare and the comparatively low emissions per kg of product are the most striking example of this phenomenon.

As described briefly in Section 2.1.5, estimates of nitrogen (N), phosphorus (P), and potassium (K) fertilization specific to each crop type were drawn from the literature (Wang et al. 2014, Xia and Yan 2011). Water use estimates are also specific to each crop type, and are based on blue water consumption, which includes both ground and surface water. The use of soil water is not considered in this study as agricultural systems tend to yield greater flows to blue water systems than the natural ecosystems that they replace (Huang et al. 2013). As a conservative estimate, all irrigation water is considered to be consumed in this study.

Nitrogen losses to air and water are particularly dependent upon management and environmental factors. Nitrogen leaching rates are a function of fertilizer application rates, methods of soil incorporation, soil type and quality, precipitation rate, and temperature (Gao et al. 2016). Several methods have been used to estimate nitrogen runoff based on applied fertilizer. The simplest methods assume that a fraction of the applied nitrogen makes it into waterways. It is suggested that dryland crops in China lose approximately four percent of applied nitrogen to leaching (Hu et al. 2011). The work of Wang et al. (2014) develops a regression equation for nitrate, N_2O, and ammonia losses due to fertilization. This equation, originally developed for use with maize in China, is used to calculate nitrogen emissions for all dryland crops in both India and China, using crop- and country-specific fertilization rates. A similar approach is used to calculate N_2O and ammonia emissions from rice production (Xia and Yan 2011). Information on the above calculation procedures is included in SI5.

No feasible method for calculating phosphorus runoff was discovered on the basis of applied fertilizer. Therefore, estimated values found in the literature specific to each crop are incorporated into the LCI. Low, average, and high estimates of yield are used to calculate a range of potential phosphorus runoff values. Phosphorus adsorbs to soil particles much more strongly than does nitrogen, and it can build and persist in the soil over many years. Although some fraction of adsorbed phosphorus is expected to be lost through windborne erosion, an estimate of this value is not included in the LCI.

Methane production is a serious concern during the production of rice using flooded fields. This study uses the IPCC (2006) method to estimate a range of potential CH_4 emissions for rice production. A base CH4 emission factor (kg per day) is adjusted using scaling factors associated with length of growing season, water regime, and the incorporation of crop residues. Detailed calculation of CH4 emissions during rice production is provided in SI5.

3.3.2 Allocation to Biogas and Bioslurry

Bioslurry[1] refers to the residual solids that remain following feedstock degradation to biogas in an anaerobic digester (AD). In a cooking system based on biogas, animal manure and other organic wastes are diverted from alternative pathways into the digester. These alternative pathways could include direct incorporation of residues or manures into the soil, composting, or use of residues as fuel or fodder. This project focuses on the use of cattle dung as an AD feedstock.

An LCI of bioslurry was created to facilitate the allocation of environmental impacts from ADs between both biogas and bioslurry. The cut-off method, which is used as the baseline modeling convention in both Phase I and II, assumes that 100 percent of the impacts associated with biogas production are allocated to the cooking fuel. Given the potential alternative uses of bioslurry listed above, there is a strong case to be made for allocating a portion of AD operational impacts to the bioslurry, as well as to the biogas. This study employs economic allocation and system expansion as part of a sensitivity analysis to quantify the effect of allocation on the environmental impacts of biogas production. Physical allocation is not considered, as it does not provide an accurate representation of the comparative value of the products.

3.3.2.1 System Expansion

Biogas is the main product, with bioslurry and its land application considered as a valuable co-product. Both the impacts of bioslurry land application and avoided fertilizer production are considered within the biogas unit process. Determination of the avoided products is addressed for N, P, and K content individually with urea, single-superphosphate, and potassium chloride being used as avoided products for each nutrient, respectively. By including a separate avoided product for each nutrient individually, it is possible to exactly match the nutrient content contained in the bioslurry with that present in the avoided products. Several studies have shown that the fertilizer value of nutrients derived from bioslurry are comparable to those supplied by commercial fertilizers (Nkoa 2014, Mikled et al. 2002).

3.3.2.2 Economic Allocation

No market price for either biogas or bioslurry is available. In the absence of a market value for biogas, a substitute value was calculated based on the price per MJ delivered for LPG. Low, medium, and high substitute value estimates for bioslurry are calculated based on a range of fertilizer values and bioslurry NPK content. The average nutrient content of bioslurry was used to perform the allocation. If packaged for sale, the nutrient content of bioslurry would read 7:4.4:4.9, corresponding to N, P_2O_5, and K_2O content as a percentage of dry weight, respectively. Assumed fertilizer and LPG prices are presented in SI7.

[1] List of additional terms for bioslurry: biogas digestate, fermenter slurry, biogas slurry, and digested slurry.

Calculated Allocation Factors

Calculated allocation factors for India and China are presented in Table 3-17 and Table 3-18. Details regarding allocation factor calculation are included in SI7.

Table 3-17. Allocation Percentages between Bioslurry and Biogas in India

Allocation Approach	Biogas	Bioslurry
Cut-off Method	100%	0%
Economic Allocation, slurry low	88%	12%
Economic Allocation, slurry high	20%	80%
Economic Allocation, average	55%	45%

Table 3-18. Allocation Factors for Biogas and Bioslurry in China

Allocation Approach	Biogas	Bioslurry
Cut-off Method	100%	0%
Economic Allocation, slurry low	85%	15%
Economic Allocation, slurry high	16%	84%
Economic Allocation, average	51%	49%

3.3.3 Biogas and Bioslurry LCI discussion

This section describes the bioslurry LCI data that are allocated as part of the sensitivity analysis. An uncertainty range associated with each LCI entry is employed to capture the variation that is inherent in both biogas and bioslurry production and use.

Bioslurry is a good source of NPK. Additionally, it provides some micronutrients necessary for plant production such as zinc and manganese. In addition to the positive components of bioslurry, there are concerns about the heavy metal content of some manures and the bioslurry that is produced from them. Estimates of nutrient, micronutrient, and the heavy metal content of bioslurry that would be applied to agricultural fields are included in the LCI

During AD operation, between 20 and 30 percent of the organic matter is converted into biogas. This change in mass is the direct consequence of biogas production, and it is reported that between 0.19 and 0.67 cubic meters of biogas are produced per kg of dry matter exiting the AD (Kalia and Singh 1998, Singh et al. 2014a, Adelekan 2014, Plochl and Heirmann 2006, Poeschl et al. 2012).

Bioslurry can also vary widely in its nutrient content. For example, values found in the literature suggest that the nitrogen content of digested slurry can vary between 0.05 and 1.8 percent of bioslurry mass on a wet basis (Gurung 1997 and Kumar et al. 2015, respectively). These values depend upon variables such as feed quality, cattle health, and dung water content to name but a few (Nkoa 2014). Controlling for variation in water content is particularly important.

All LCI values have been standardized to the dry matter content of the bioslurry when it exits the AD. In some cases, the dry matter content of a sample is not reported, and when this is true, the average dry matter content of the bioslurry profiles compiled has been applied so that the information can be included in the LCI.

There are also many elements of AD operation and bioslurry management that ultimately affect nutrient availability to agricultural crops. After being expelled from the animal, nitrogen starts being lost through ammonia volatilization. Time to collection, weather, and storage practices can greatly affect these losses (Nkoa 2014). Little nitrogen is generally assumed to be lost during the actual process of anaerobic digestion. However, one source reported a potential loss between three and ten percent of total nitrogen content (Gurung 1997). Further losses to volatilization can come during subsequent storage of the digested slurry or during and immediately following field application. The amount of time elapsed, application method, extent of soil incorporation, temperature, and precipitation all have a significant effect on loss rates following digestion. The literature suggests that ammonia losses of 20 to 35 percent are possible during field application alone (Makadi et al. 2012).

These losses, apart from the minor losses in the digester itself, are also applicable to other forms of organic and inorganic fertilizer that may be used as an alternative to bioslurry. Quantitative evaluation of the average relative losses between various fertilizers and application methods is beyond the scope of this analysis. However, we discuss the ways in which the AD affects both rates of volatilization and plant utilization efficiency.

Contradictory results are present in the literature regarding the relative potential nutrient losses of digested and undigested slurry. Most references reviewed indicate that the digestion process increases the potential for ammonia volatilization due to its increased share of the nitrogen fraction and the increase in pH associated with digestion[2] (Nkoa 2014). Others suggest that undigested slurry[3] tends to lose more nitrogen to volatilization during field application while digested slurry loses more during storage (Smith et al. 2007). The authors hypothesize that the decreased solids content of digested slurry allows quicker infiltration, thereby reducing volatilization after field application. On average, the digestion process increases the ammonium (NH_4^+) content of bioslurry, in relation to the fresh manure that was used as a feedstock, by 25 percent (Arthurson 2009). Ammonium is one of two plant-available forms of nitrogen, the other being nitrate (NO_3).

Many authors have used the increased share of total nitrogen attributable to ammonium to suggest that rates of nutrient utilization are higher for bioslurry as compared to rates in un-digested manure. The work of Smith et al. (2007) suggests that while a higher rate of nutrient utilization for bioslurry may be true in the short-term, in the long term the relative rate of nutrient utilization evens out between digested and undigested manure because, over time, nitrogen in un-digested manure is mineralized and becomes available to plants. A good number of other studies indicate that the fertilizer value of bioslurry is greater than (Somasundaram et al. 2007, Mikled et al. 2002, Ahmad and Jabeen 2009) or equal to (Haraldsen et al. 2011, Nkoa 2014) that of a comparable quantity of manure or mineral fertilizer. In this study, we consider that the

[2] Not all references support this supposed increase in pH (e.g., Smith et al. 2007)

[3] Manure mixed with water.

fertilization value of digested manure, undigested manure, and commercial fertilizers is equivalent per unit of applied nutrient. The organic matter content of both digested and undigested manure is expected to improve soil tilth and moisture retention when compared to mineral fertilizer applications. However, this benefit is not quantified.

The research of Smith et al. (2007) also indicates that there is no discernible effect of slurry digestion on annual emission of N_2O, a potent greenhouse gas. N_2O emissions are considered to be equivalent between digested and undigested slurry per kg of applied nitrogen. Other authors have shown that the use of digested slurry leads to reduced N_2O emissions per unit of applied nitrogen (Nkoa 2014). The range of this reduction was between 17 and 71 percent (Borjesson and Berglund 2006). The absolute level of these reductions is highly dependent upon soil type, application method, and local weather, as is the magnitude of N_2O emissions generally. The work of Koster et al. (2015) indicates that lower N_2O emissions are due to the lower amount of labile carbon that is available for denitrification in digested cattle waste[4].

Finally, this study considers the differential effect of digestion on the potential for nutrient runoff from agricultural fields, and again the results are mixed. The review by Nkoa (2014) suggests that given the state of current research, we can expect similar nitrogen runoff emissions at a given application rate regardless of fertilizer type. Nitrate nitrogen is the predominant species contributing to nitrogen runoff. Ammonium, on the other hand, is a minor contributor, which indicates a low potential for short-term increase in nitrogen runoff attributable to the ammonium increase during digestion. However, this ammonium can oxidize to nitrate over time.

In general, phosphorus runoff is determined by soil type, application rate, and weather conditions following application (Radcliffe et al. 2015). No references specific to bioslurry field application have been found to indicate that there is an expected influence on phosphorus leaching to surface and groundwater beyond what is typical for other phosphorus additions.

3.3.4 Electricity from Ethanol Production

Electricity is often a co-benefit of ethanol production. The Phase I study did not include a credit for grid electricity displaced by electricity co-produced with ethanol. Inclusion of this credit, by application of the system expansion modeling approach, could decrease the overall environmental impacts for ethanol. Bagasse at the mill provides excess energy that can be exported as electricity. A sensitivity analysis covers incorporation of the electricity credit of the electrical grid mix for the relevant country. Ethanol is assumed to be produced from molasses. Refined sugar is also an output of molasses production. In all cases, the allocation between molasses and sugar is conducted on a mass basis.

[4] Soil carbon is necessary for cell growth during denitrification.

4. METHODOLOGY FOR RESULTS COMPILATION

This section discusses key methodological considerations for transforming the LCI data compiled into the environmental impact results presented in this report.

4.1 Biogenic Carbon Accounting

In biomass fuel systems, CO_2 is removed from the atmosphere and incorporated into the plant material that is harvested from the forest or field. This (biogenic) carbon is stored in the material throughout the life of the product until that fuel is combusted or degrades, at which point the carbon is released back into the environment. Combustion and degradation releases are predominantly in the form of CO_2 and CH_4. This study, in alignment with the IPCC methodology, assumes a zero net impact for biogenic carbon that is removed from the atmosphere in the form of CO_2 and later returned to the atmosphere (e.g., as CO_2 emissions from the combustion of biomass cookstove fuels). That is, if the carbon removed from the atmosphere is returned to the atmosphere in the same form, the net impact GCCP is zero. Impacts associated with the emission of biogenic carbon in the form of CH_4 are included since CH_4 was not removed from the atmosphere and its GCCP is 28 times that of CO_2 when applying the IPCC 2013 100a LCIA method. The one exception is the CO_2 emissions from non-renewable wood fuel associated with deforestation in the four countries assessed and, therefore, long-term reduction of global CO_2 sinks. The method used to calculate the non-renewable portion of wood for cooking fuel is described in the next section.

4.2 Non-Renewable Wood Fuel Calculations

In the GHG analysis, the carbon dioxide emissions for the portion of biomass fuel from unsustainable wood supplies are considered non-renewable and are therefore incorporated into the overall GCCP results. This phase of work uses the methodology described by Bailis et al. (2015) to calculate forest renewability factors. Using the Yale Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM) database (Drigo 2014), the Bailis method developed a spatially explicit assessment of woodfuel supply and demand based on the relative woody biomass supply and regrowth compared to demand. The Bailis study found its results for non-renewable forestry were lower than those previously published in the literature. Phase I of the cookstoves research relied on the renewable wood calculation outlined by Singh and colleagues (2014a), which is described in subsequent paragraphs. Table 4-1 lists the Phase I and Phase II baseline forest renewability factors. Because the methods for determining such renewability factors are novel and uncertain, a sensitivity analysis is included in this study to assess the effect of methodology assumption on overall results.

Table 4-1. Phase I and II Forest Renewability Factors

Country	Phase II Forest Renewability Factor (% renewable)	Phase I Forest Renewability Factor (% renewable)
India	76.3	59.2
China	77.8	57.5
Kenya	36.1	0
Ghana	70.6	0

Using the Singh method, the biomass stock in m^3 for each country (from FAO 2010 Table 10) was multiplied by the regional factor for tonnes of above-ground biomass (AGB) per m^3 (from FAO 2010 Table 2.18) to calculate the tonnes of AGB. The amount of below-ground biomass (BGB) was calculated by multiplying the tonnes of AGB by the regional factor for BGB/AGB (from FAO 2010 Table 2.18). The amount of dead wood was then calculated using the regional factor for dead-to-live biomass ratio (from FAO 2010 Table 2.18) applied to the total AGB and BGB. Next, the average annual increase or decrease in forest land for each country was calculated based on the carbon stocks in living forest biomass reported for each country in 2000 and 2010 (from FAO 2010 Table 11). The annual firewood supply potential for each country was then calculated as the total weight of AGB and dead wood multiplied by country-specific factors for the percent accessibility to forests (from the Yale WISDOM Database (Drigo 2014)) and the country-specific average annual change in forest land.

The annual demand for firewood cooking fuel (tonnes) for each country was calculated based on the country-specific cooking energy demand per household multiplied by the number of households using wood for cooking fuel, divided by the cooking energy per kg of firewood (calculated as the lower heating value of firewood multiplied by stove efficiency). For India, 11.0 MJ of cooking energy are consumed per household per day (Habib et al. 2004), with 105 million rural households and 16 million urban households using wood for cooking fuel (Singh et al. 2014a). In China, 13.6 MJ of cooking energy are consumed per household per day (Zhou et al. 2007), with over 131 million rural households and over nine million urban households using wood for cooking according to World Bank statistics. In Kenya, 12.5 MJ of cooking energy are consumed per household per day (IEA 2014, GVEP International 2012a), with over five million households using wood for cooking (GVEP International 2012b). In Ghana, 13.6 MJ of cooking energy are consumed per household per day (IEA 2014, with almost three million households using wood for cooking (GVEP International 2012c). Finally, the renewable percentage of cooking firewood was calculated as the annual firewood supply potential divided by the total annual demand for cooking firewood. The percentage of annual firewood demand that cannot be met by the annual firewood supply potential was considered non-renewable.

4.3 Black Carbon and Short-Lived Climate Pollutants Calculations

This section summarizes key physical parameters considered in the approach to include the differences in potential amounts of BC, OC, and other co-emitted species produced from use of the investigated cookstove/fuel technologies. BC and co-emitted species are formed by combustion of fossil and bio-based fuels (e.g., diesel, coal, crop residues).

Per the Gold Standard Framework method (GSF 2015), fuel production, transport, and consumption life cycle phases are included in the inventory and impact assessment. An inventory of BC and OC is based on the quantity of PM (less than or equal to 2.5 microns of aerodynamic diameter-$PM_{2.5}$) released for each inventory step in the cookstove fuel/technology life cycle. In many cases, LCI data sources do not specify the type of PM emissions (e.g., outputs are reported as ‘particulate matter’ or ‘particulate matter, unspecified’). For upstream process inventories where PM emission speciation is not provided, no BC and/or OC emission factors are applied. However, co-emitted species emission factors for these processes are included. In the foreground cookstove fuel combustion, BC and OC emission factors based on quantity of PM released (e.g., per fraction reported as $PM_{2.5}$) are applied. Where no size distinctions between PM emissions have been made in LCI data sources, all PM emissions from fuel combustion are assumed to be of the fine particle variety (e.g., of less than or equal to 2.5 microns in size).[5]

Carbon in $PM_{2.5}$ emissions takes the following forms: 1) organic carbon; 2) elemental carbon (EC), which usually includes soot; and 3) carbonate ion (CO_3^{-2}). Methods that measure light absorption in $PM_{2.5}$ assume that the light absorbing component is BC and partitioning of EC and OC is somewhat arbitrary. Though some components of OC may be light-absorbing (e.g., brown carbon or BrC), most researchers presume that OC possesses light-scattering properties (e.g., producing climate cooling effects). Because there is high uncertainty and lack of consensus on the ratio of the BrC class of OC particles for each fraction of OC, analyzing impacts of BrC in OC is excluded in this analysis and instead, focus is placed on the EC or soot portion and the OC portions of the $PM_{2.5}$ emissions. In other words, BC emissions may be estimated by assuming that only the EC portion of the $PM_{2.5}$ emissions contributes to BC release and subsequent positive radiative forcing, while OC emissions are assumed to contribute to negative radiative forcing. This approach requires estimating the $PM_{2.5}$ emission amount and source-specific EC-to-$PM_{2.5}$ and then the BC-to-OC ratio for each of the fuel/stove technologies being investigated in the study.

Potential climate forcing impacts resulting from BC/OC and co-emitted species include direct, albedo, and other indirect effects. Overall, most estimates indicate BC yielding a net warming effect on climate, but co-emitted species can have some offsetting effects, as discussed below. Species co-emitted with BC/OC such as CO, NMVOCs, NOx, and SO_2 are precursors to the formation of sulfate and/or organic aerosols in the atmosphere. These aerosols affect reflectivity and other cloud properties and have a cooling affect.

BC and other short-lived climate pollutants (SLCPs) such as the aforementioned co-emitted species are distinguished from other climate-forcing emissions (e.g., GHGs) in that their atmospheric lifetime is not as long-lived, so potential impacts are estimated on a shorter time-scale and can be very geographic and seasonally dependent (unlike long-lived, well-mixed GHGs). However, short-lived forcing effects of BC are substantial compared to effects of long-lived GHGs from the same sources, even when the forcing is integrated over 100 years. The GCCP of BC and co-emitted species included in this approach are calculated using GCCP 20-year BC eq. factors from IPCC 2013 as summarized in Table 4-2.

[5] Per (2008) "Secondary PM and combustion soot tend to be fine particles ($PM_{2.5}$), whereas fugitive dust is mostly coarse particles".

Table 4-2. Characterization Factors for BC eq

	Included in GSF 2015	GCCP (20) per IPCC 2013	BC eq
Warming Effects	BC	2421	1
	NOx	16.7	0.00690
	CO	5.9	0.002
	NMVOC	14	0.006
Cooling Effects	OC	-244	-0.1
	SO4 (-2)	-141	-0.058

Source: GSF 2015.

4.4 LCA Model Framework

All LCI unit processes developed for this work (summarized in SI1-SI7) are intended for publication in the US Federal LCA Digital Commons Life Cycle Inventory Unit Process Templates (in Microsoft Excel® format) (United States Department of Agriculture (USDA) and U.S. EPA 2015). To build the life cycle model, the unit processes were entered into the open-source openLCA software (Version 1.5.0, GreenDelta 2016. Quality assurance (QA) reviews were completed for the openLCA model to ensure that all inputs and outputs, quantities, units, and metadata were correctly entered. Associated metadata for each unit process are recorded in the openLCA unit processes.

Once all necessary data were imported into the openLCA software and reviewed, system models were created for each fuel and country combination. The models were QA-reviewed to ensure that each elementary flow (e.g., environmental emissions, consumption of natural resources, and energy demand) was characterized under each impact category for which a characterization factor was available. The draft final system models were also QA-reviewed prior to calculating results to make certain all connections to upstream processes and weight factors were valid. LCIA results were then calculated by generating a contribution analysis for the selected fuel product system based on the defined functional unit of 1 GJ of delivered heat for cooking.

4.5 Monte Carlo Uncertainty Analysis

An important issue to consider when using LCI study results is the reliability of the data. In a complex study with literally thousands of numeric entries, the accuracy of the data and how it affects conclusions is truly a complex subject, and one that does not lend itself to standard error analysis techniques. Techniques such as Monte Carlo analysis can be used to study uncertainty, but a lack of uncertainty data or probability distributions for key parameters, which are often only available as single point estimates, continues to pose a challenge.

Monte Carlo analysis is a statistical procedure used to simulate the potential range of results in each impact category based on underlying uncertainty distributions attached to individual flows of input materials, energy, and emissions to nature. Five thousand simulations were conducted for each stove grouping based on the distributions associated with each flow value. The important concept that is highlighted by the uncertainty analysis is that for any study dealing with a general functional unit such as the national average GJ of delivered heat from a given stove grouping, there is not one number that accurately quantifies environmental impact. Instead, multiple parameters can be varied at once to estimate the potential range in environmental impact scores. Stove emission and crop production uncertainty information incorporated in the Monte Carlo analysis are described below. Ranges on other parameters (e.g., emissions from the charcoal kiln and from bioslurry land application) are applied to the uncertainty analysis as well.

4.5.1 Uncertainty Modeling Documentation

Stove Uncertainty

Stove use phase emission estimates are a compilation of emission testing results from the literature as reported in Table 2-1. Emission values from these studies are classified into stove groupings defined by fuel type, stove type, and country. Stove use phase emissions are modeled using a lognormal distribution. For emissions that have six or greater recorded emission estimates for a given stove grouping, the geometric standard deviation of the emission values is used in the Monte Carlo analysis. For each country and pollutant combination, a proxy standard deviation is calculated based on the stove grouping with the greatest recorded number of emission estimates. This value is used for stove groupings that have less than six recorded emission estimates for a given pollutant in combination with the geometric average of the available emission values. The range of recorded stove thermal efficiencies is used in combination with the fuel LHV to calculate a triangular distribution for stove fuel, ash production, transport, and other associated inputs and outputs. A geometric standard deviation of 1.05 is used for embodied energy flows that contribute to CED. Table 4-3 lists factors expected to contribute to uncertainty in the cookstove emissions data.

Table 4-3. Sources and Mechanisms of Uncertainty in Cookstove LCIs

Category	Source	Mechanism
Fuel Characteristics	Heat Content	Specific fuels used in the emissions studies used to compile stove emission LCIs vary over a given range.
	Moisture Content	Moisture content is variable for a given fuel type and affects thermal and combustion efficiency.
Stove Characteristics	Thermal Efficiency	Varies over a given range within the assigned stove groupings.
External Factors	Operator Practice	Fuel placement, ventilation control, cooking pot, and cooking practices affect thermal transfer and combustion efficiency.
	Climate	Humidity, wind, and air temperature affect combustion and thermal transfer of heat.
Combustion	Emissions	Testing uncertainty. Should be a dependent factor.

Crop Residue Production

Description of national average crop production practice and environmental impact is a particular challenge. Table 4-4 lists parameters that contribute to uncertainty in estimates of national average crop production. Multiple estimates were sought for each LCI flow. All input and output flows were recalculated so that they are reported per kg of crop produced. The average of these values is taken as the average flow value used in the baseline results. To cover the widest possible range of uncertainty, a national estimate of low and high yield for each crop is used to recalculate the LCI flow per kg of crop production. The lowest and highest values for each LCI flow are taken as the lower and higher ends of a triangular distribution, while the average value is taken as the peak, or most likely, flow. This approach assumes that even the lowest fertilization rate can correspond to the highest yield, or that the highest fertilization rate can correspond to the lowest yield. This assumption is justifiable in light of the independent nature of many of the factors that affect crop yields and thereby impacts per kilogram of crop production. Any single agricultural practice, no matter how ideal, cannot guarantee a successful crop. Appropriate rates of fertilization and pest management can be undone by an early frost or lack of rain. While this assumption holds in any given year, it is expected that over the long run the lowest and highest values cannot persist and that impacts tend towards the average.

Table 4-4. Sources and Mechanisms of Uncertainty in Crop Production

Category	Source	Mechanism
Location Dependent	Climate	Temperature, day length, precipitation patterns, and the frequency of extreme weather events all have a direct effect on crop yields and emissions to air that is independent of agricultural inputs applied.
	Soil Type	Varies widely within a country or region and has a direct effect on crop yields and emissions to air and water that result from fertilizer application.
	Topography	Affects erosion and runoff rates which has an indirect effect on emissions to land and water.
Management	Farm Size	The range of farm sizes within a given nation has a direct effect on the level of mechanization, soil management practices, and a range of other factors that affect the quantity of agricultural inputs, emissions, and yields.
	Crop Variety Selection	Selection of varieties within a given crop type (e.g., maize, rice) affect the necessary rates of irrigation and fertilization at a given location. For rice, variety selection is of particular importance to CH4 emissions where the time to maturity and inundation requirements have a direct relationship to CH4 production.
	Farming Practice	A wide range of production methods exist at the national level. Heavy tilling, no-till, organic production, and pesticide application are a few of the production practices that can affect LCI input and output values.

4.6 Normalization

Normalization is a process of standardizing impact scores in all categories so that the relative contribution of impact scores associated with the functional unit can be judged relative to total national or global emissions contributing to impacts in a given category. Table 4-5 lists normalization factors for each country and impact category. Normalization allows us to better assess the significance of impact categories by comparing to benchmarks at the national level.

Table 4-5. Country Specific Normalization Factors (per person per year)

Impact category	Unit	India		China		Kenya		Ghana	
		Factor	Source	Factor	Source	Factor	Source	Factor	Source
Global Climate Change	kg CO_2 eq	6,890	1	6,890	1	6,890	1	6,890	1
Energy Demand	MJ	28,300	2	96,000	2	19,600	7	14,800	9
Fossil Depletion	kg oil eq	1,290	1	1,290	1	1,290	1	1,290	1
Water Depletion	m^3 eq	631	3	408	3	52.2	3	52.2	3
Particulate Matter Formation	kg $PM_{2.5}$ eq	14.1	1	14.1	1	14.1	1	14.1	1
Photochemical Oxidant Formation	kg NMVOC eq	56.7	1	56.7	1	56.7	1	56.7	1
Freshwater Eutrophication	kg N eq	0.29	1	0.29	1	0.29	1	0.29	1
Terrestrial Acidification	kg SO_2 eq	38.2	1	38.2	1	38.2	1	38.2	1
Ozone Depletion	kg CFC-11 eq	0.04	1	0.04	1	0.04	1	0.04	1
Black Carbon and Short-Lived Climate Pollutants	kg BC eq	0.92	4,5	1.44	6	1.36	8	3.33	8

Sources: [1] Goedkoop et al. 2008, [2] adapted from Enerdata 2016, [3] adapted from FAO 2016, [4] adapted from Sloss 2012, [5] adapted from Paliwal et al. 2016, [6] adapted from Wang et al. 2012, [7] adapted from IEA 2016, [8] adapted from U.S. EPA 2012, [9] adapted form GEC 2015

Normalized results are calculated by multiplying environmental impact per GJ of cooking energy by national cooking energy expenditures (Table 4-6) and dividing by the appropriate normalization factor from Table 4-5. This calculation produces results in units of person equivalent emissions for all impact categories. Normalized results scaled by country-specific cooking energy use provide key context for the relative changes in impacts from shifting fuel choice under specific future cooking fuel mix scenarios.

Table 4-6. Household Energy Use for Cooking per Year

Country	GJ/Household/year	Sources
India	4.02	Habib et al. 2004 per Venkataraman et al. 2010
China	4.95	Zhou et al. 2007[1]
Kenya	4.56	IEA 2014, GVEP 2012a
Ghana	4.96	IEA 2014
Country	**# Households**	**Sources**
India	267,006,110	calculated
China	437,741,935	ASTAE 2013
Kenya	8,870,000	calculated
Ghana	6,475,000	calculated
Country	**Household Size (ppl.)**	**Source**
India	4.91	Dalberg 2013b
China	3.1	TekCarta 2015
Kenya	5	GVEP International 2012a
Ghana	4	ADP 2012

Notes: Ppl = number of people; values may be converted from original source to be shown on an annual basis.
[1] Includes energy for both cooking and water heating from Table 7 of Zhou et al. 2007. Values combined for urban and rural population based on population statistics in WorldBank 2013.

4.7 Results Presentation Format

Results presented in Sections 5 through 8 of this report do not include all possible results tables and figures for each impact category. Rather, the report includes a more focused analysis on new information associated with Phase II. The full breadth of information generated from this study is available in the appendices and SI1-7 (see SI file descriptions in Section 1.3.3), including country-specific Excel® workbooks that contain all of the results and figures available. Each workbook presents results for both individual fuels and current and potential fuel mixes. Within the workbook, custom fuel mix, stove technology mix, stove efficiency, electricity grid mix, LCA modeling approach, and forestry renewability fraction can be customized by the user to compare the associated changes in environmental impacts. The charts that are included in each results workbook are described below:

- **Single Fuel Results by Impact Category** – Bar charts present impact scores broken down by life cycle stage for each cooking fuel type. Results for each cooking fuel type are aggregated according to stove technology mix, stove efficiency, electricity grid mix, and forest renewability fraction, which can be customized by the user.

- **Single Fuel Results as a Percent of Maximum Impact[6]** – Bar charts show the impact of each fuel type relative to the fuel with the greatest impact in each category. Results are aggregated according to the life cycle stage in which they occur.

[6] Results are dependent on the underlying stove technology mix, stove efficiency, electricity grid mix, LCA modeling approach to allocation, and forest renewability fraction.

- **Relative Fuel Mix Scenario Results[6] –** Aggregate impact scores for both current and potential fuel mixes are presented relative to the cooking fuel mix with the greatest impact score in each category. Results are depicted according to cooking fuel type.
- **Fuel Mix Scenario Results[6] –** Bar charts compare fuel mix impact scores for both current and potential fuel mixes, aggregated according to fuel type.
- **Normalized Results[6] –** Bar charts show person equivalent emissions for each impact category presented according to fuel type.
- **Stove Uncertainty Analysis Results** – Impact scores for each stove group are presented according to impact category with error bars showing the estimated uncertainty range for each stove.
- **Stove Efficiency Sensitivity –** A bar chart shows comparative results for both current and future improved stove thermal efficiency assumptions for each stove group.
- **Electricity Grid Sensitivity –** Comparative results for the electric cooking stove are presented according to the underlying electricity grid mix. Users are able to toggle between current and future improved stove thermal efficiency and impact category assessed.
- **Cooking Scenario Sensitivity –** Bar charts show the comparative effect on aggregate fuel mix impact score from the range of available stove technologies, stove thermal efficiencies, and electrical grid mix selections. Results are aggregated according to fuel type.
- **Forest Renewability Fraction Sensitivity** – A bar chart shows the comparative effect of the assumed forest renewability fraction on impact scores for stove groups where fuel is derived from forest products.
- **LCA Modeling Sensitivity –** A bar chart shows the comparative effect of LCA modeling choices for selected cooking fuels. Results are presented separately for each impact category.

LCIA results for ten impact categories were calculated for this study. Summary discussion and figures for each country include results for all impact categories. Detailed discussion and figures focus on the following four impact categories:

- Global Climate Change Potential
- Cumulative Energy Demand
- Particulate Matter Formation Potential
- Black Carbon and Short-Lived Climate Pollutant Potential.

The above impact categories were selected due either to general interest or their strong connection with the cooking sector as revealed in the normalized results analysis. This selection is not meant to imply that other impact categories are of less importance. Select results for impact categories, beyond the four impact categories listed above, are included within the sensitivity and uncertainty analysis results sections to highlight trends of interest and to demonstrate the full breadth of results available in the SI. The presentation of results in Sections 5 through 8 provides a foundation on which interpretation of results for other impact categories, reported in the results workbooks, is possible. All readers are encouraged to explore the full range of results for all impact categories.

Baseline LCA results highlight the general trends in environmental impact associated with different cooking fuel mix interventions. The uncertainty and sensitivity analyses provide a measure of how robust these trends are and the actual gains that could be made by adopting various strategies designed to reduce emissions and increase efficiency in the generation and use of household cooking energy.

While the study has justified its specification of the fuel mix scenarios included, these cooking fuel mix scenarios are not intended to strictly define perception of what is either possible or most likely. All results should be viewed as a starting point for understanding current environmental impacts in relation to future possibilities, with an eye towards what is technically possible, and a focus on identifying key levers that are available to achieve improvement in the environmental and human health outcomes of the cooking sector.

5. UPDATED LCA RESULTS FOR INDIA

Table 5-1 presents summarized India LCA results for all cooking fuel types and impact categories on the basis of 1 GJ of cooking energy delivered. The results are representative of baseline assumptions concerning cooking fuel mix, stove technology use, stove thermal efficiency, electricity grid, and forest renewability factor. A discussion of notable changes between results for Phase I and Phase II is provided Appendix B. Table 5-1 displays baseline LCA results for all investigated current and projected Indian cooking fuel types, currently nearly 70 percent of India's population relies on firewood, dung cake, and crop residue to provide their cooking energy (Dalberg 2013b), and most households still rely on traditional mud stoves to consume these fuels (Smith et al. 2000).

The remainder of this chapter focuses on quantifying the environmental impact of interventions for India's cooking fuel mix through actions such as changing the cooking fuel types in the country-wide mix, adopting improved stoves, improving overall stove efficiency, and shifting the fuel type and associated technology used for India's electrical grid. The results also identify which of the environmental impact categories assessed contribute the most to Indian economy-wide impacts. Select uncertainty results and sensitivity analyses are presented to increase understanding of the level of confidence readers should have in the LCA results by cooking fuel type.

Table 5-1. Summary Table of Single Fuel Results by Impact Category (Impact/GJ Delivered Cooking Energy) - India

Fuel Type	GCCP	CED	FDP	WDP	PMFP
	(kg CO_2 eq)	(MJ)	(kg oil eq)	(m^3)	(kg PM10 eq)
Hard Coal	963	7.21E+3	172	0.397	19.8
Dung Cake	263	1.30E+4	0.152	1.68E-3	24.3
Crop Residue	119	1.01E+4	7.90E-3	8.72E-5	11.4
Firewood	196	6.52E+3	5.94E-3	6.54E-5	5.54
Charcoal from Wood	402	1.09E+4	0.011	1.20E-4	20.5
Kerosene	180	3.09E+3	70.9	0.239	0.171
LPG	157	2.61E+3	58.7	0.193	0.136
Natural Gas	117	2.04E+3	48.7	0.039	0.019
Electricity	457	5.70E+3	122	3.25	1.91
Sugarcane Ethanol	121	1.33E+4	31.0	643	4.38
Biogas from Cattle Dung	11.4	4.06E+3	-	1.02	0.210
Biomass Pellets	141	3.91E+3	13.72	0.357	0.302

Table 5-1. Summary Table of Single Fuel Results by Impact Category (Impact/GJ Delivered Cooking Energy) - India

Fuel Type	POFP (kg NMVOC)	FEP (kg P eq)	TAP (kg SO_2 eq)	ODP (kg CFC-11 eq)	BC (kg BC eq)
Hard Coal	7.87	2.37E-3	1.87	3.01E-8	4.10
Dung Cake	18.8	0.189	0.736	1.40E-9	5.27
Crop Residue	8.22	9.80E-3	0.598	7.28E-11	2.48
Firewood	5.38	7.36E-3	0.377	5.46E-11	1.22
Charcoal from Wood	10.4	0.014	0.209	1.03E-10	4.58
Kerosene	0.481	3.77E-3	0.291	6.20E-8	0.021
LPG	0.341	3.37E-3	0.256	6.56E-8	0.012
Natural Gas	0.046	7.05E-5	0.027	7.25E-8	2.07E-3
Electricity	2.66	3.75E-3	4.54	4.24E-7	-0.016
Sugarcane Ethanol	0.633	0.038	4.35	2.82E-6	0.757
Biogas from Cattle Dung	0.114	-	0.106	-	0.035
Biomass Pellets	1.520	0.006	0.502	5.31E-8	0.026

5.1 Cooking Fuel Mix Scenario Results – India

Cooking fuel mix scenario results provide the most comprehensive perspective on the options for cookstove sector improvements included in Phase II of this work. Figure 5-1 shows the effect of various model parameters on climate change impacts per GJ of cooking energy delivered for India. Figure 5-1 also serves as a model for interpretation of subsequent figures in this section. At the top of the figure is the baseline (current) fuel mix applying the best available estimate of current stove technology use and stove thermal efficiency. Results for potential fuel mix scenarios evaluated are presented according to a series of four technology options, as described in Table 5-2.

Table 5-2. Cooking Fuel Mix Scenario Technology Options (*Figure Key*)

Fuel Mix Scenario Axis Labels	Description
Current Tech-Current Eff-Current Grid[1]	Assumes current stove technology, current average stove thermal efficiency values, and 2013 electrical grid mix.
Imp Tech-Current Eff-Current Grid	Assumes improved stove technology use, current average stove thermal efficiency values, and 2013 electrical grid mix.
Imp Tech-Imp Eff-Current Grid	Assumes improved stove technology use, improved stove thermal efficiency values, and 2013 electrical grid mix.
Imp Tech-Imp Eff-Clean Grid	Assumes improved stove technology use, improved stove thermal efficiency values, and the use of clean electricity in electric cookstoves.

[1] Tech = stove technology, Imp = improved, Eff = stove efficiency

The current cooking fuel mix in India yields a GCCP of just below 200 kg of CO_2 equivalent emissions per GJ of delivered cooking energy. Baseline cooking fuel mix results for all other countries analyzed in this study exceed 375 kg of CO_2 equivalent emissions. The figure demonstrates that realizing further GCCP impact reductions will be a challenge for India as the country moves to adopt modern, fossil-based cooking fuels. This result is largely because firewood and crop residue, which together comprise just under 60 percent of the current cooking fuel mix, each have among the lowest single fuel GCCP impact scores of the commonly used fuels. As discussed in Section 4.1 and Section 4.2, 100 percent of CO_2 combustion emissions associated with crop residue and 76 percent of CO_2 combustion emissions associated with firewood are considered to be from renewable biomass and therefore do not contribute to the overall GCCP impact. The previous assumption for firewood is based on the Phase II baseline forest renewability factor, which is subject both to uncertainty and the potential to change over time. Increases in electricity use that do not assume reliance on a cleaner electricity grid lead to increases in fuel mix GCCP. In general, scenarios that include appreciable quantities of electric stove use are quite sensitive to the underlying electrical grid mix assumption. A maximum 33 percent reduction in GCCP is realized by the Diverse Modern Fuel mix scenario assuming adoption of improved stove technology, improved stove thermal efficiency, and a clean electricity grid.

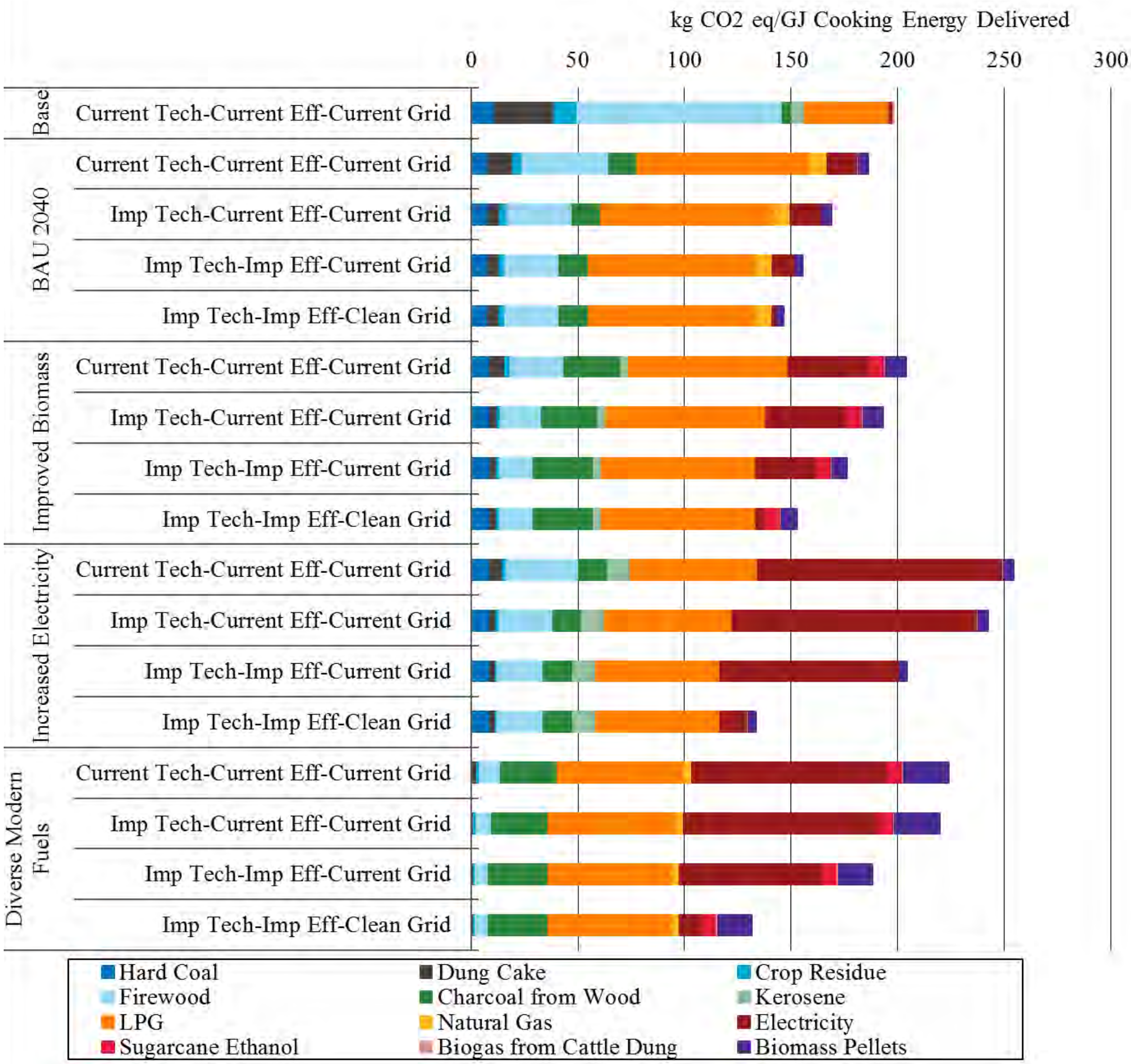


Figure 5-1. India GCCP cooking fuel mix scenario results.

(Axis abbreviations: Imp = improved, Tech = stove technology, Eff = stove efficiency)

Figure 5-2 presents PMFP cooking fuel mix results for India. In the current fuel mix scenario, the traditional fuels contribute the vast majority of particulate matter emissions. All four future cooking fuel mix scenarios propose reductions in the use of traditional fuels, which leads to a minimum 46 percent reduction in PMFP impacts across all scenarios relative to the baseline. Including the possibility of stove technology upgrades increases the range of impact reductions to between 58 and 64 percent, depending upon the scenario. Within a given cooking fuel mix, the adoption of improved stove technology and thermal efficiency is responsible for between six and 19 percent of the total reduction in impact score. Cooking fuel mixes that rely more heavily on traditional fuels benefit the most from stove technology and efficiency upgrades. Figure 5-2 shows that the modest increases in charcoal use explored in the Improved Biomass, Increased Electricity, and Diverse Modern Fuel mix scenarios contribute disproportionately to fuel mix PMFP impact, over 90 percent of charcoal's PMFP impact is due to kiln emissions. BC impact results, provided in Appendix A, follow a trend very similar to those exhibited by PMFP in Figure 5-2.

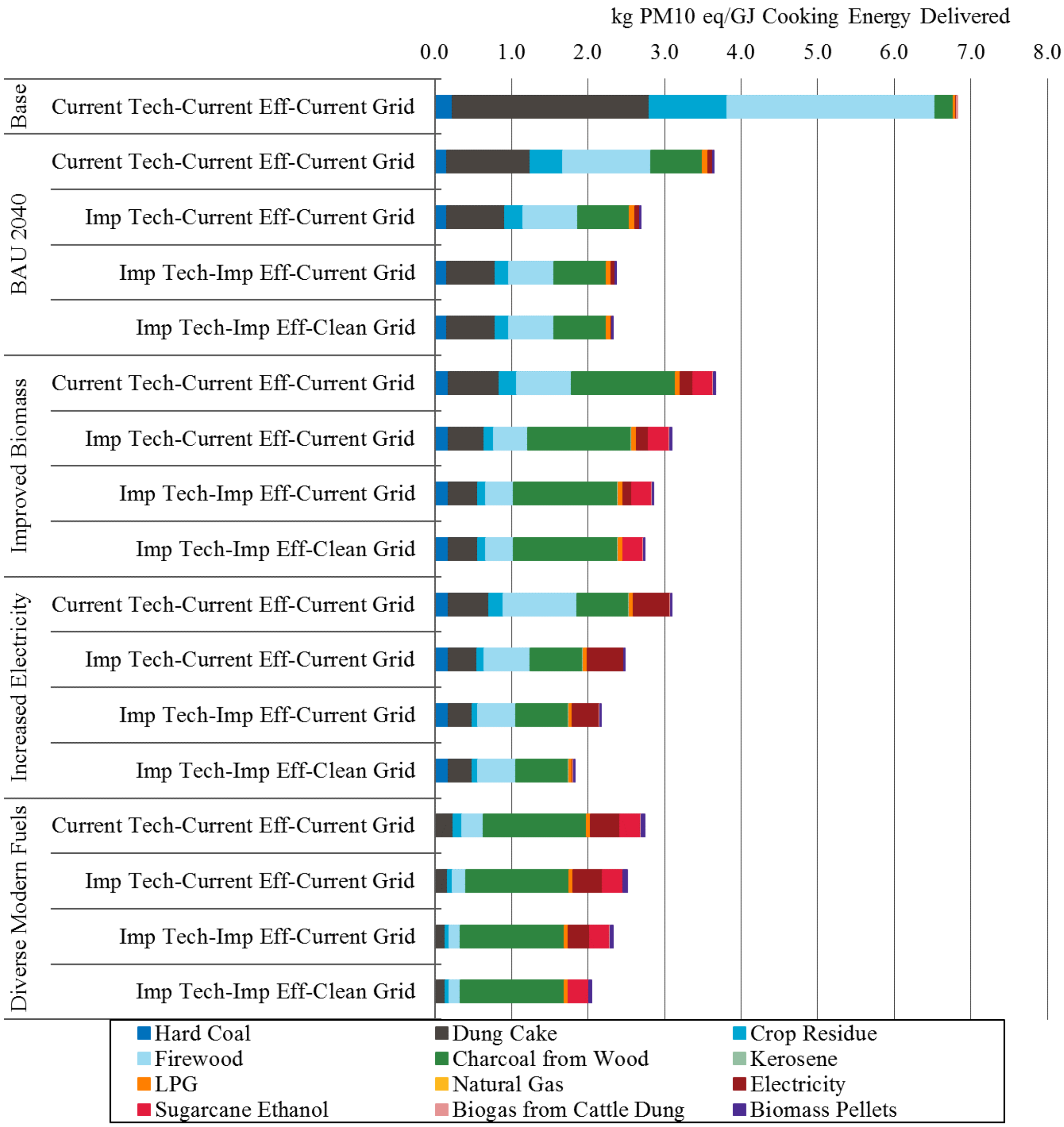


Figure 5-2. India PMFP cooking fuel mix scenario results.

(Axis abbreviations: Imp = improved, Tech = stove technology, Eff = stove efficiency)

As demonstrated in Figure 5-3, CED is greatest for the baseline scenario. Energy demand in the baseline scenario is largely driven by the low thermal efficiency of traditional cookstoves used to burn firewood, dung, and crop residue. The modest increase in reliance on charcoal and sugarcane ethanol present in both the Improved Biomass and Diverse Modern Fuel scenarios is clearly visible in the figure due to inefficient energy conversion in these fuel types' respective supply-chains. In the absence of stove technology improvements, the projected fuel mix scenarios yield CED reductions between 20 and 29 percent, compared to the baseline scenario. Further CED reductions (between 31 and 44 percent compared to the baseline scenario) can be realized when the effect of stove technology and efficiency improvements are included. Modern liquid/gas fuels and biomass pellets demonstrate the lowest CED of the cooking fuel types considered for India.

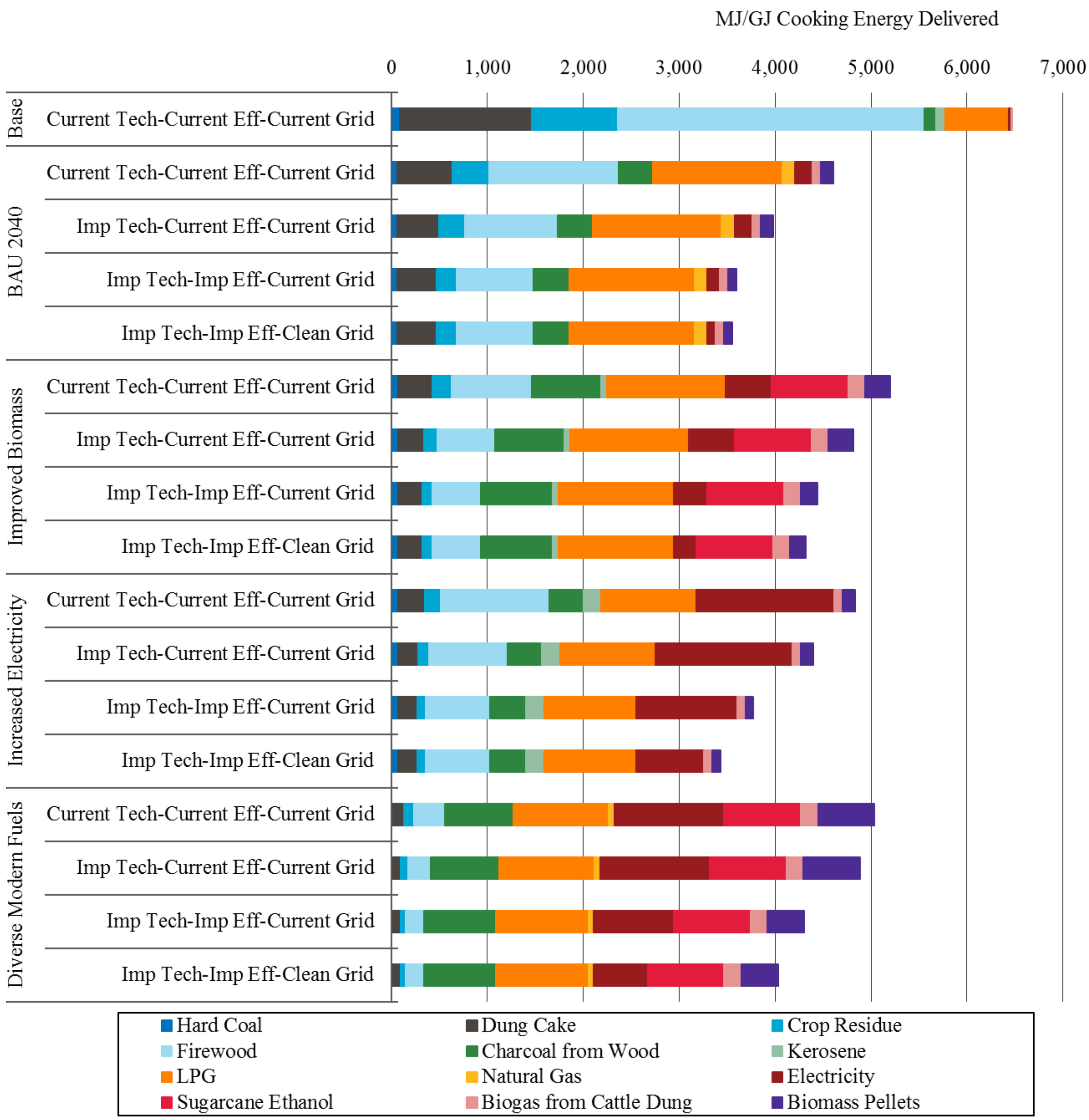


Figure 5-3. India CED cooking fuel mix scenario results.

(Axis abbreviations: Imp = improved, Tech = stove technology, Eff = stove efficiency)

5.2 Baseline Normalized Results – India

The concept and methodology behind presenting normalized results are discussed in Section 4.6. Generally, normalized results show which impact categories are most strongly linked to the activity under study. If normalization factors were perfectly calibrated, the sum of personal equivalent emissions for all sectors in the economy would equal the population of a given country, which for India is approximately 1.3 billion people. However, normalized emission estimates are uncertain due to lack of geographic granularity and the ever-changing nature of national or global level estimates for many categories, indicating that the relative magnitude of results (and not the specific person equivalency value) is of greater importance and validity. Normalized results only indicate the contribution level of the cookstove sector to national economy-wide impacts. Normalized results do not imply that impact categories are of greater or lesser significance.

Normalized results for India are presented in Figure 5-4. PMFP, CED, and BC impact categories all show a strong dependence on activity in the cooking sector at a national level. The importance of the cooking sector to these impact categories indicates an opportunity to reduce national environmental impacts by way of interventions in the cooking sector. Mitigating combustion emissions associated with traditional biomass fuels through adoption of improved stoves or decreasing the overall reliance on traditional biomass cooking fuels would lead to the largest reductions in normalized results in India.

Normalized BC impacts exceed the expected maximum of 1.3 billion person equivalents, likely due to a number of factors, including the large negative BC impact that is associated with coal-based electricity production in India. To make up for this negative forcing, the total of other sectors must be greater than 100 percent of net national characterized BC emissions. The uncertainty of the BC impact assessment and emission inventories could also account for a portion of the observed phenomena.

The figure shows very low normalized impacts of the cooking sector on ODP. Other impact categories show only modest contributions from the cooking sector, indicating that between two and six percent of national emissions in each category are associated with household cooking.

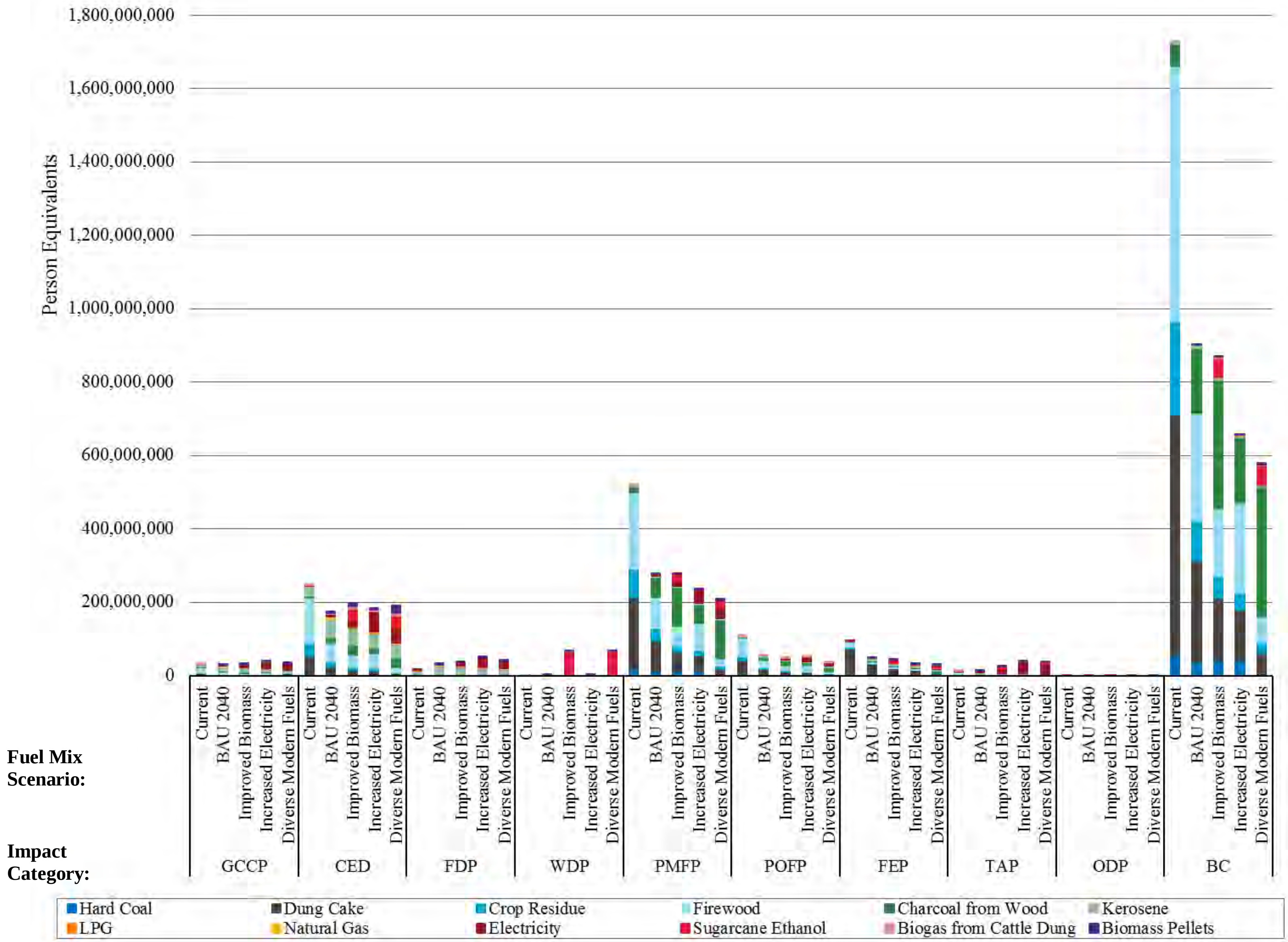


Figure 5-4. India normalized LCIA results.

5.3 Stove Efficiency Sensitivity – India

Figure 5-5 presents the effect of stove thermal efficiency improvement on PMFP of select cookstoves in India. Each of the bars is labeled with the associated current or future, improved stove thermal efficiency value for that stove group. The figure shows that fuel type is the greatest determinant of PMFP impact among the traditional fuels in India. It is not possible, for example, for dung cake burned in an improved cookstove to become a competitive option with either crop residue or firewood regardless of the stove type used to burn these fuels. The figure also shows that the movement from traditional to improved cookstoves provides more substantial reductions in PMFP than does seeking the best possible thermal efficiency from traditional stoves. Promotion of the highest possible thermal efficiency for improved cookstoves can yield appreciable reductions in environmental impact as evidenced by the best performing crop residue and firewood improved cookstoves realizing 24 and 17 percent reductions in PMFP, respectively, relative to the current average thermal efficiency for these two stove groups.

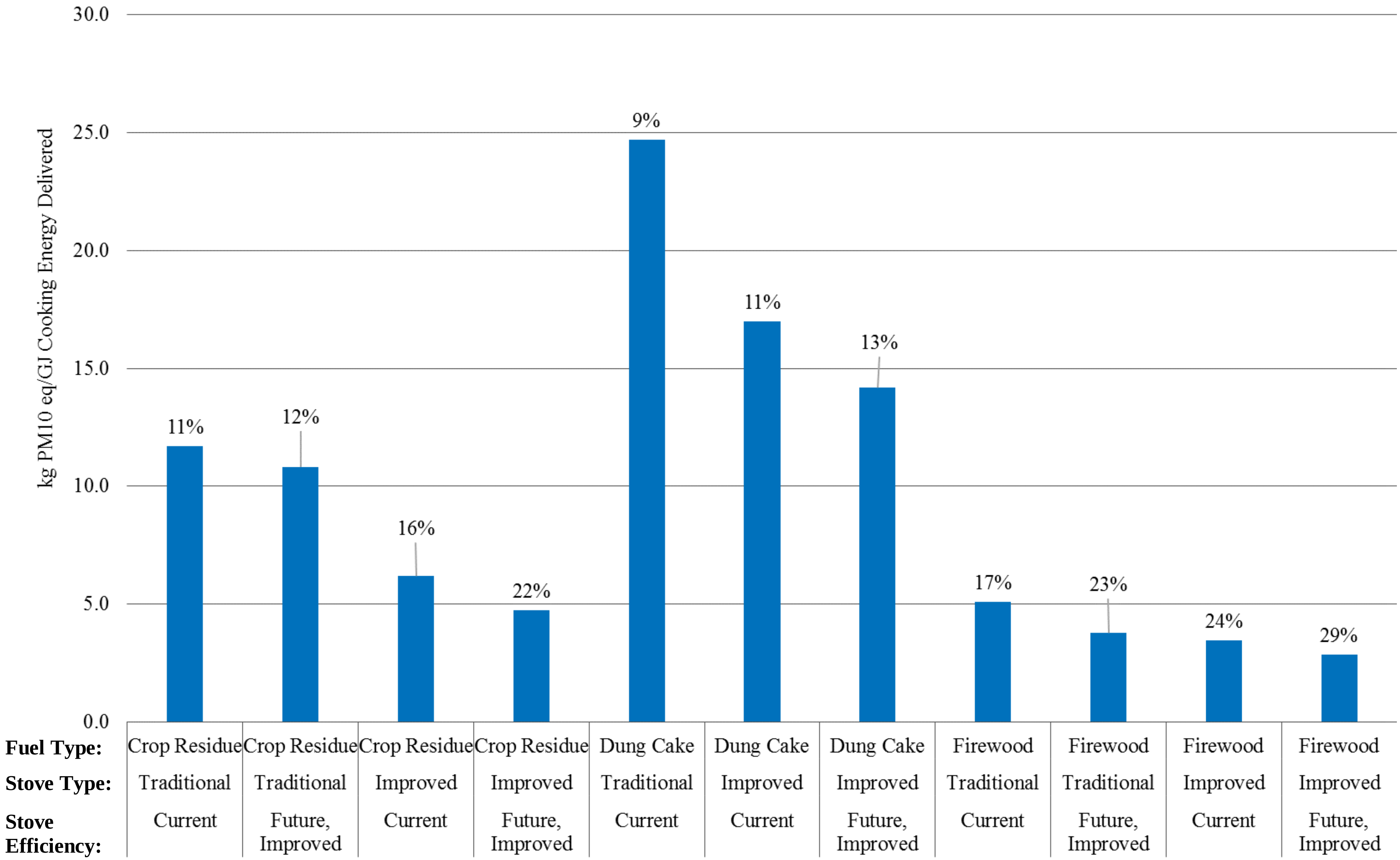


Figure 5-5. Effect of stove thermal efficiency improvement on PMFP traditional cooking fuel results in India.

Figure 5-6 presents the effect of stove thermal efficiency improvement on CED of select cookstoves in India. Each of the bars is labeled with the associated current or future, improved stove thermal efficiency value for that stove group. CED is less strongly determined by fuel type than is PMFP as is visible from a comparison of Figure 5-5 and Figure 5-6. Results for CED, like PMFP, show that the movement to improved cookstoves still has more potential for environmental impact reduction than is possible from stove thermal efficiency improvement within a given stove type; however, the percent reductions in CED due to upgrades from improved to traditional stoves are less dramatic than those demonstrated for PMFP because the overall percent difference in CED between traditional and modern fuels is lower than that observed for PMFP. Comparatively, the reductions in CED attributable to the assumed stove thermal efficiency improvements are roughly equivalent to the reductions for PMFP, 24 and 17 percent for improved crop residue and firewood stoves, respectively.

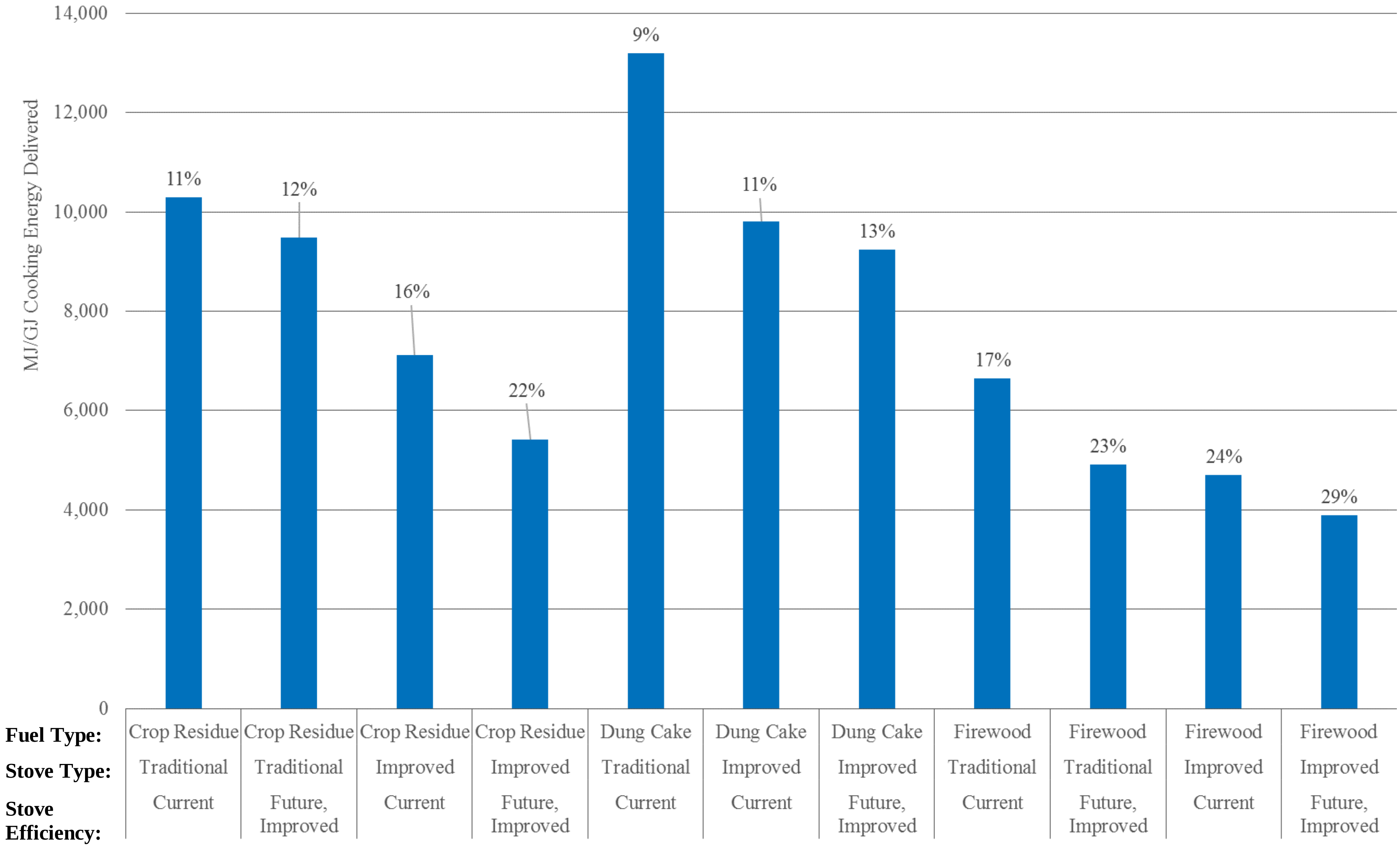


Figure 5-6. Effect of stove thermal efficiency improvement on CED: traditional cooking fuel results in India.

5.4 Electrical Grid Mix Sensitivity – India

Figure 5-7 shows the effect of the underlying electrical grid mix on GCCP of electric cookstoves in India. Based on the modeled changes to the electrical grid between 2013 and 2021, the GCCP of electric cookstoves can be reduced by between 16 and 33 percent. As demand for electricity increases beyond 2021, it is possible that the carbon footprint of electricity production could again increase as high carbon sources may be required to satisfy the growth in demand. CED, FDP, WDP, PMFP, POFP, and Terrestrial Acidification Potential (TAP) all follow a trend similar to GCCP.

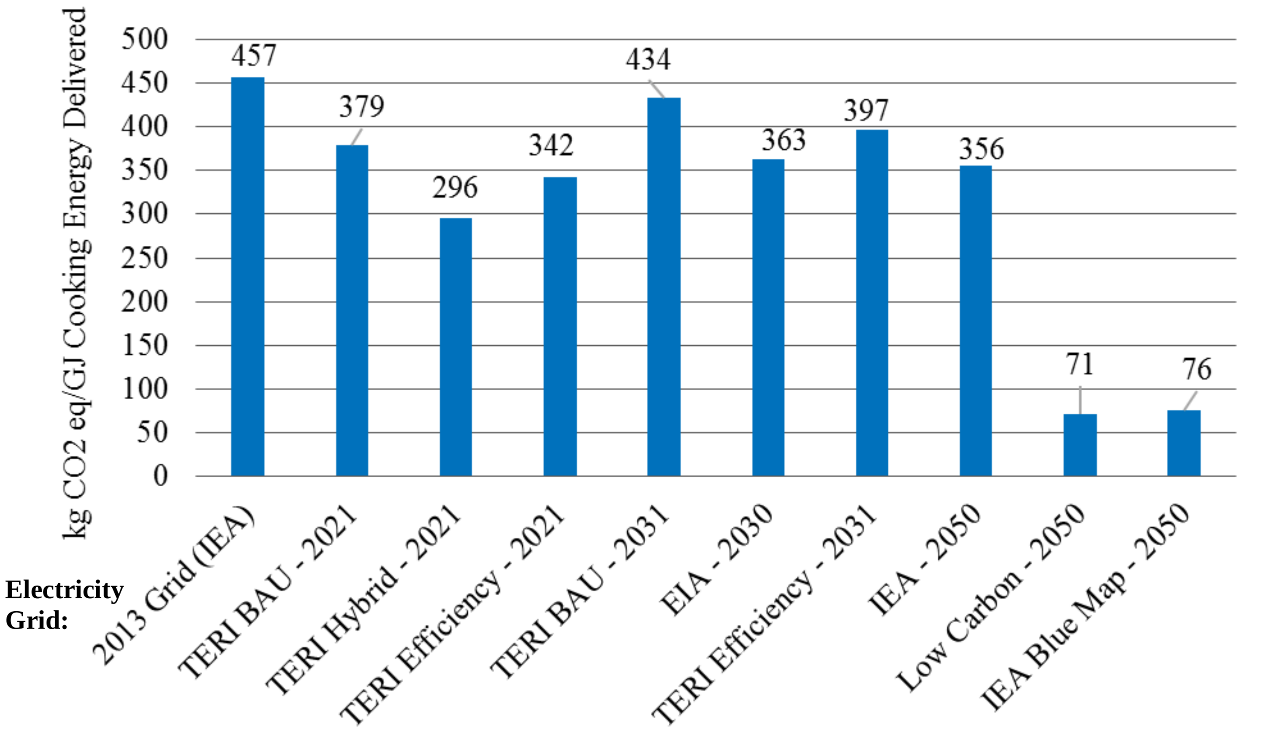


Figure 5-7. Effect of electrical grid mix on GCCP impact of electric cookstoves in India.

BC impacts, as shown in Figure 5-8, tend to increase as the electrical grid mix moves away from coal-based power generation and relies more heavily on other fuels. The TERI Efficiency-2031 scenario still uses a significant amount of coal, but relies heavily on IGCC technology that produces far lower sulfur dioxide emissions, resulting in a higher BC impact score. Sulfur emissions associated with coal combustion generate a short-term cooling effect that is responsible for the negative impact scores visible in the figure.

FEP and ODP impacts are highest for both the Low Carbon and IEA Blue Map grids. Increases in ODP potential are contributed by solar, nuclear, and natural gas electricity generation. Increases in FEP are due to the production of the electronic components in solar panels.

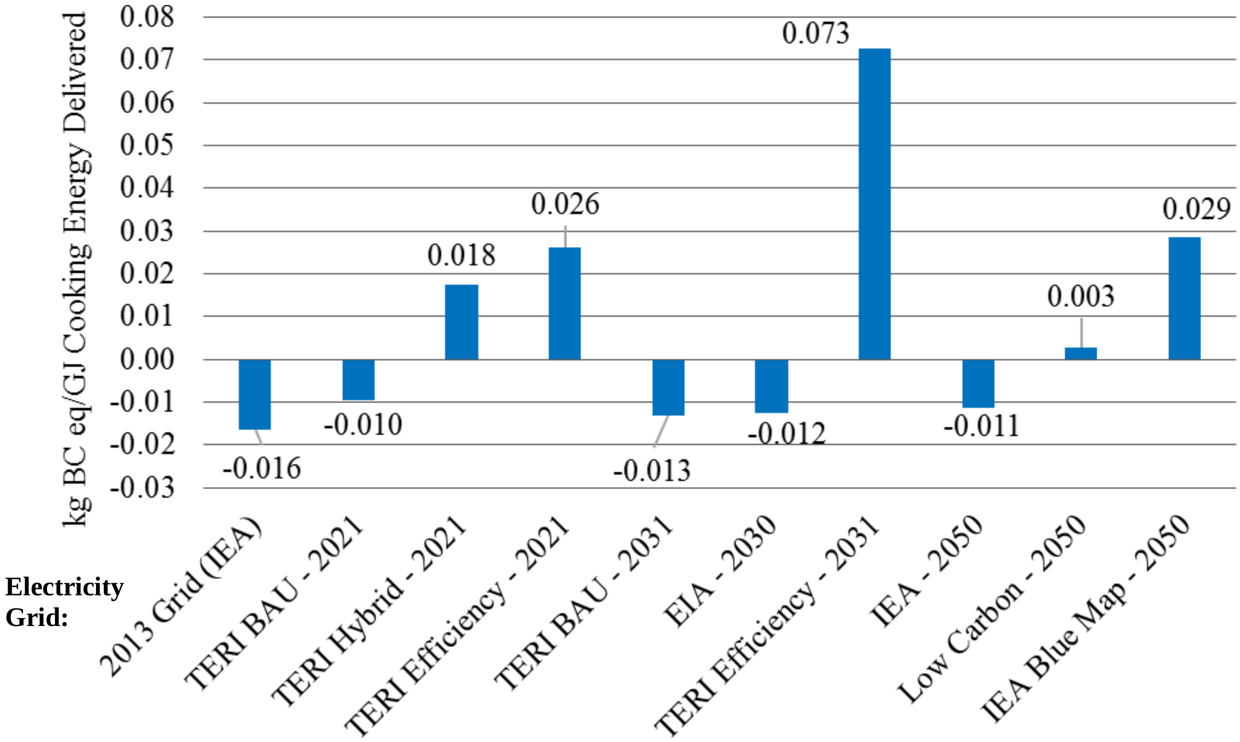


Figure 5-8. Effect of electrical grid mix on BC impact of electric cookstoves in India.

5.5 Forest Renewability Factor Sensitivity – India

The use of two separate methodologies, previously described in Section 4.2, to determine the fraction of forestry products that are renewably produced and are therefore carbon neutral leads to an approximate 16 percent difference in the estimate of total forest products that are derived from sustainable operations (Figure 5-9). The baseline value for Phase II of this study is derived from the WISDOM database (Drigo 2014) and leads to reductions in GCCP impacts of between 25 and 35 percent when compared to the low renewability factor that served as the baseline value for Phase I of this work. When analyzing both single-fuel and cooking fuel mix scenario results, the low renewability factor provides a stronger justification (from a climate change perspective) for the promotion of modern liquid/gas fuels as a replacement for firewood.

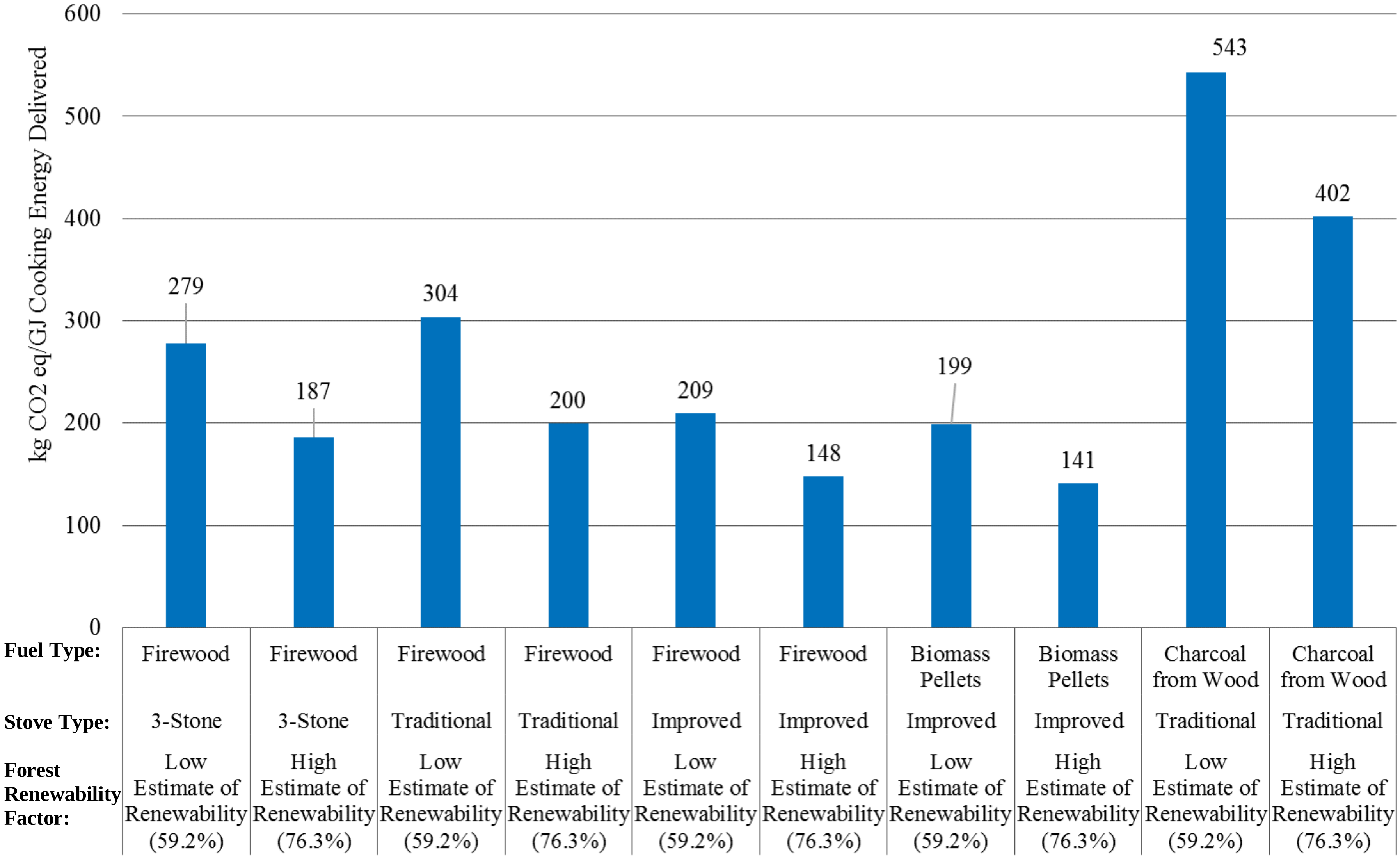


Figure 5-9. Comparative effect of forest product renewability assumption on GCCP in India.

5.6 Allocation Approach Sensitivity – India

This section describes the effect of LCA modeling conventions on cookstove environmental impacts for crop residue, biogas, and sugarcane ethanol. The crop residue allocation issue centers on the question of how best to distribute environmental impacts of agricultural production between food crops and other forms of agricultural biomass such as straw and stover. For biogas, the modeling question concerns how to allocate impacts of anaerobic digester operation between the biogas and the digestate. Sugarcane ethanol modeling choices concern both the agricultural impacts of sugarcane production and how best to deal with surplus electricity generated from bagasse combustion during molasses and ethanol production. Detailed methodology options applied to address these allocation questions are outlined in Section 3.3.

Figure 5-10 shows the effect of LCA modeling choices on GCCP impact for sugarcane ethanol and biogas. The sugarcane ethanol GCCP impact is particularly sensitive to the application of system expansion, which credits the cookstove with avoided electricity production that results from combustion of bagasse, a co-product of sugarcane cultivation, during molasses and ethanol production. The magnitude of GCCP associated with avoided electricity production is enough to make the life cycle impacts of sugarcane ethanol net negative from a climate change perspective. The GCCP of sugarcane ethanol is not particularly sensitive to the choice between economic and physical allocation, which yields a six percent difference in impact score. Overall, the avoided electricity production in the ethanol supply chain has a beneficial effect on all impact categories assessed.

As is evident in Figure 5-10, the GCCP of biogas is sensitive to all three allocation modeling options. Economic allocation for biogas yields a GCCP impact score that is 46 percent lower than the score that is calculated using the cut-off method, which attributes 100 percent of anaerobic digestion impacts to biogas, thereby leaving digestate burden free. System expansion produces a net negative impact score due to avoided fertilizer production when land- applying the digestate. The same is true for FDP, WDP, POFP, and ODP. Impact categories strongly affected by land application of digestate such as PMFP, FEP, TAP, and BC all yield impact scores that are higher using the system expansion approach. Both PMFP and TAP are increased due to ammonia emissions from the field.

Figure 5-11 shows that CED is less sensitive to the choice of modeling technique than GCCP. The choice of economic allocation versus system expansion to model sugarcane ethanol production leads to a 14 percent difference in estimated CED. Use of system expansion to model biogas production yields a 38 percent reduction in estimated CED compared to the baseline, cut-off method. The effects of LCA allocation approach selection on crop residue impacts are similar for both India and China. Section 6.6 provides a detailed discussion using results for China to illustrate trends.

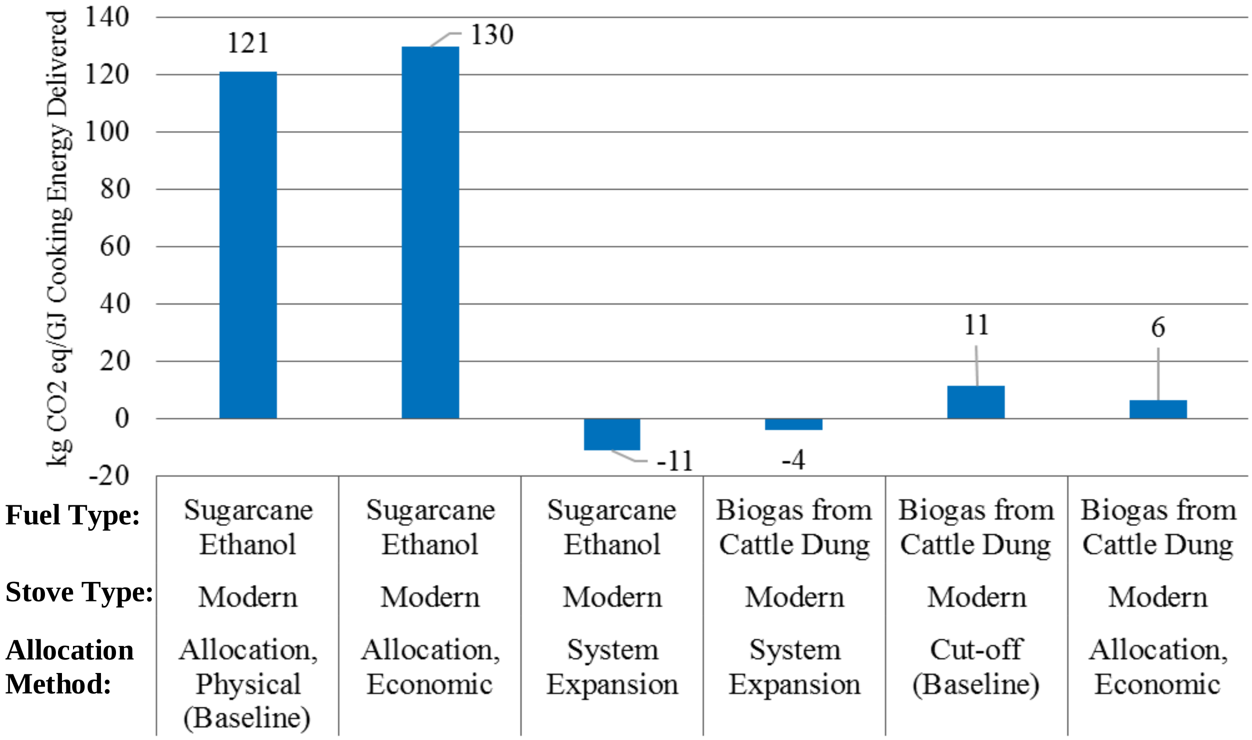


Figure 5-10. Effects of allocation methodology choice on sugarcane ethanol and biogas GCCP impact in India.

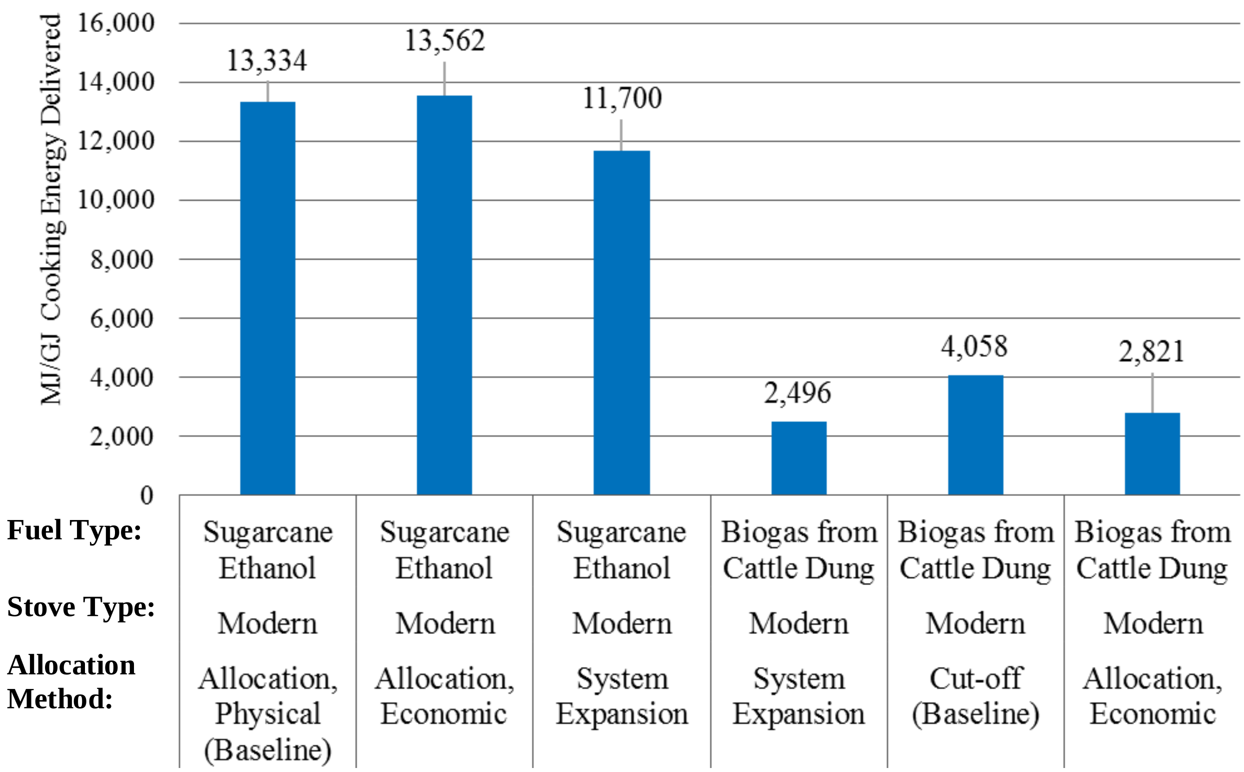


Figure 5-11. Effects of allocation methodology choice on sugarcane ethanol and biogas CED impact in India.

5.7 Stove Group Uncertainty Results – India

Figure 5-12 shows GCCP for traditional biomass fuels in India. All results in the figure represent the baseline LCA modeling convention. The height of the bar in each figure represents the Monte Carlo mean around which the error bars are centered. The analysis mean (triangle in figure) for each impact category is the characterized expected value as it was entered into the openLCA model. The analysis and Monte Carlo mean deviate from one another depending upon the distribution used, and in the case of lognormally distributed data, depending upon the geometric standard deviation.

The uncertainty range associated with GCCP of rice production has a strong effect on the impacts of cooking with crop residue if the mass ratio of production between food crops and crop residues is used to allocate the impacts of agricultural production. The height of the uncertainty band is due to the range of potential CH4 emissions associated with rice production. Methane emissions per kg of rice are dependent upon yield, duration of inundation, and incorporation of organic matter. Use of the cut-off method to model cooking with crop residue represents only the impacts of the cooking process itself and assumes that 100 percent of agricultural impacts are attributable to food crops, thereby treating crop residues as a waste or a secondary by-product that does not contribute to the demand for agricultural production. GCCP uncertainty ranges for other stove and fuel types are generally much more narrow relative to the impact score of a given stove, which improves the ability to discern true differences in the climate impact of stoves burning different fuel types, as well as between improved and traditional stoves for a given fuel. The figure shows, for example, minimal overlap between the uncertainty ranges of improved and traditional stoves burning dried dung cake, which indicates that justifiable reductions in GCCP are possible if households upgrade to improved stoves.

Figure 5-13 shows POFP impact scores for the same stoves and fuels displayed in the previous figure. Generally, the uncertainty ranges associated with the emission of volatile organic compounds, which contribute to this impact category, are wider than they are for all other impact categories in this study. This wide range obscures the ability to differentiate between certain stove-fuel combinations regarding their contribution to POFP impact. Dung cake appears to have much higher potential to contribute POFP emissions, while improved stoves burning firewood realize a significant reduction in POFP emissions as compared to other stoves burning traditional fuels.

Figure 5-14 shows WDP impact scores for the fuels that demonstrate the greatest WDP potential per GJ of delivered cooking energy. Normalized results in the previous section indicate that most fuels contribute very marginally to WDP at the national level. Figure 5-14 confirms that WDP for cooking fuels is predominantly due to the production of agricultural crops. However not all crops place similar demands on water resources. Water use of sugarcane is noticeably lower than for both rice and wheat, due to the significantly greater yield potential of sugarcane per hectare. The share of WDP that is attributed to crop residues is shown to be highly sensitive to the choice of LCA modeling technique as demonstrated by the disparity in WDP impacts between the cut-off method and physical allocation. The cut-off method attributes 100 percent of water demand to food crop production, leaving crop residues burden free.

A notable contrast from Phase I results regards the contribution of electricity production to WDP impacts. Electricity was shown to generate very high water use, largely due to turbine water use necessary for hydropower production. Phase II results are adjusted to reflect the fact that turbine water is still available for environmental use and is not considered to contribute to WDP, significantly reducing the WDP of electricity production. Hard coal is included in the figure to provide a reference point for the WDP of fossil fuels.

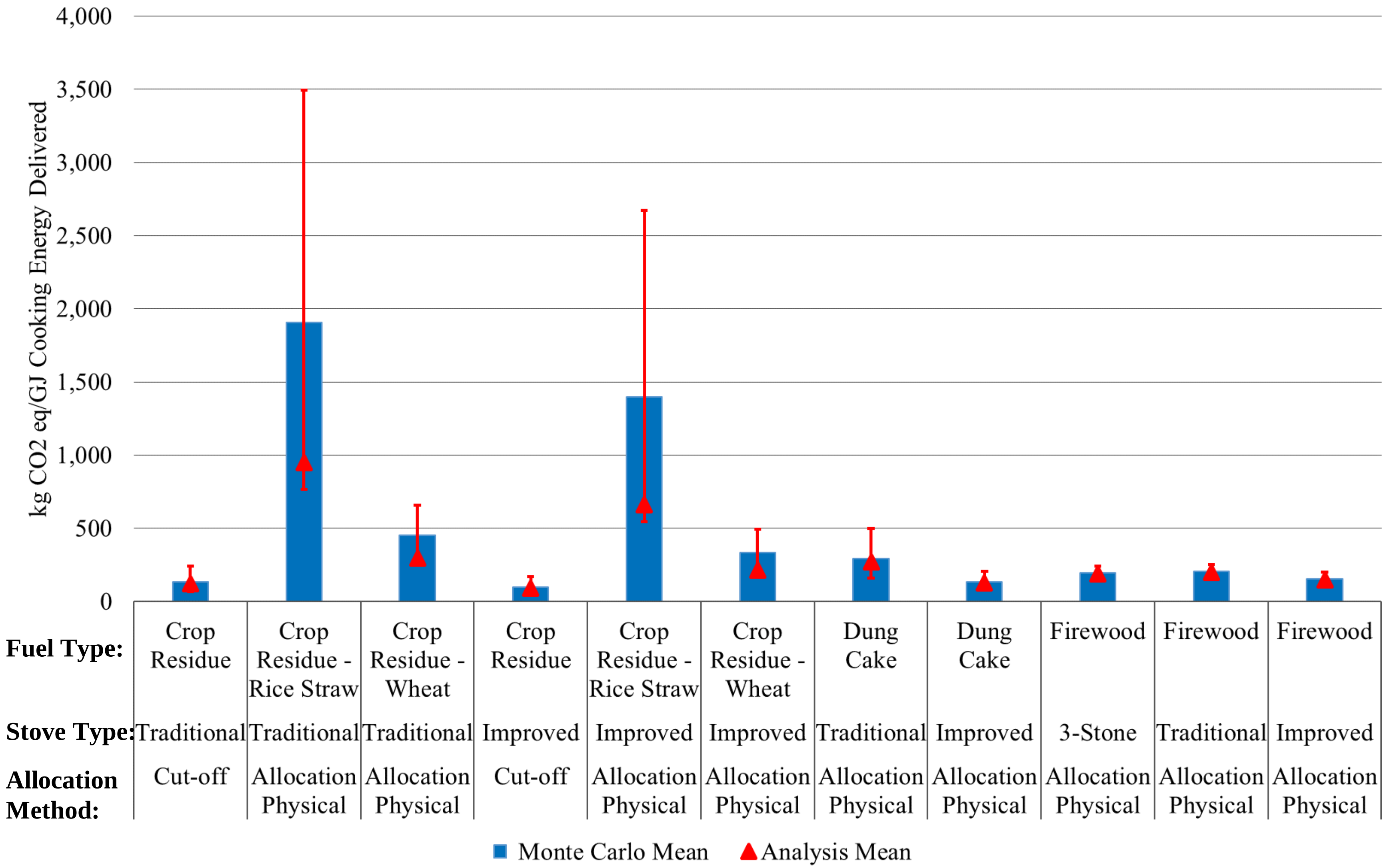


Figure 5-12. India GCCP uncertainty analysis results for traditional cooking fuels modeled with various allocation approaches and stove technologies.

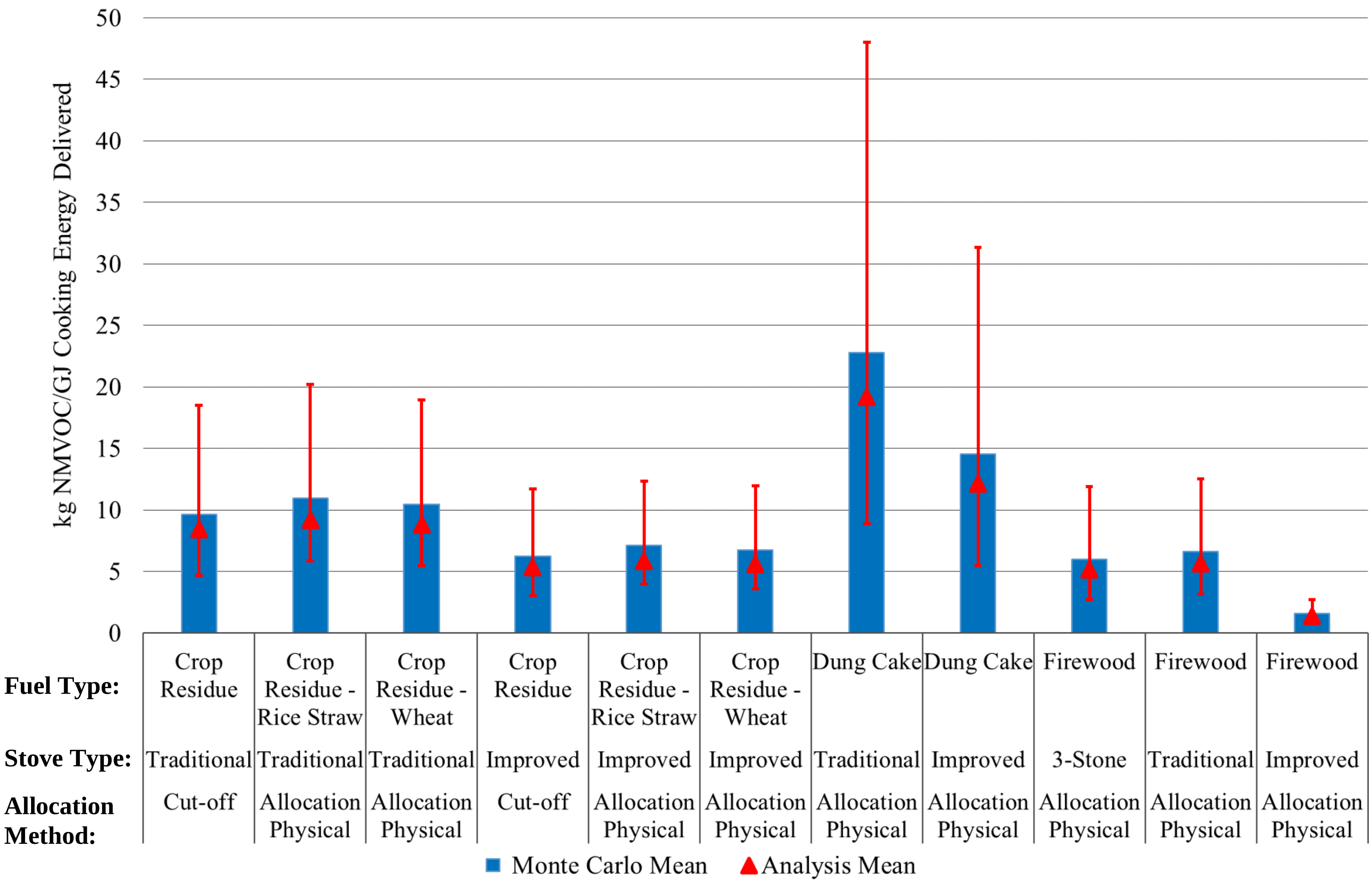


Figure 5-13. India POFP uncertainty analysis results for traditional cooking fuels modeled with various allocation approaches and stove technologies.

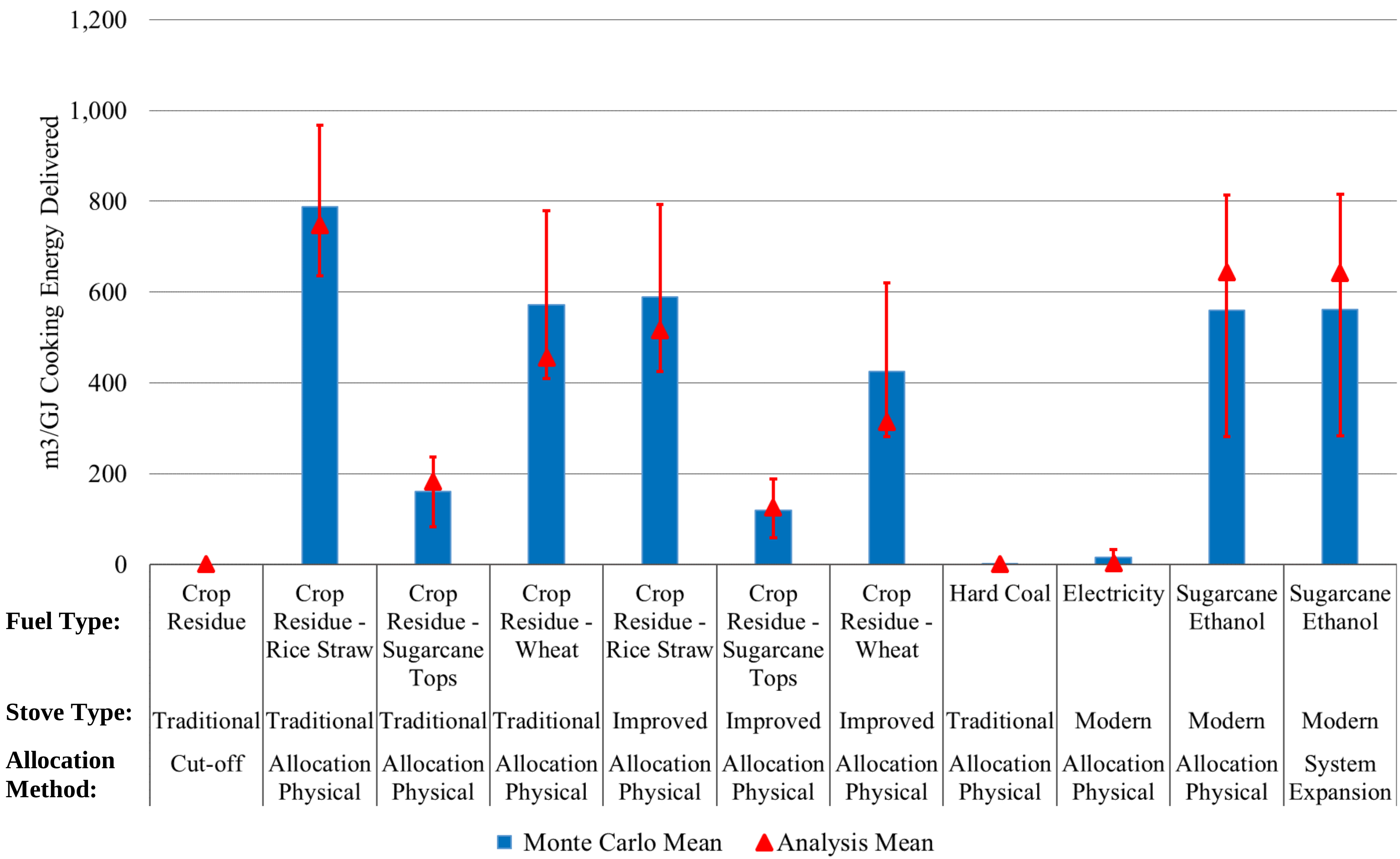


Figure 5-14. India WDP uncertainty analysis results for select cooking fuels modeled with various allocation approaches and stove technologies.

6. UPDATED LCA RESULTS FOR CHINA

In China, only 27 percent of national cooking energy is provided by traditional biomass fuels, and China is the only country studied to rely on coal for a notable portion of its cooking energy. Modern fuels such as LPG, electricity, and natural gas provide nearly 45 percent of cooking fuel, which is a higher proportion of cooking energy than is observed in other nations studied (Dalberg 2014). China is characterized by an electrical grid that is associated with high environmental impacts due to heavy reliance on coal. These aspects of the current cooking fuel mix have a significant impact on the trends observed in the LCA results for China. China is also more industrialized than the other countries studied, and therefore has a correspondingly higher national energy demand (Enerdata 2016), which impacts normalized LCA results presented in Section 6.2.

Table 6-1 summarizes LCA results for all fuel types and impact categories in China. The results are representative of baseline assumptions concerning cooking fuel mix, stove technology use, stove thermal efficiency, electricity grid, and forest renewability factor, as documented in Sections 2.2.2 and 3.1.2. A discussion of notable changes between results for Phase I and Phase II is provided in Appendix B. Various forms of coal and electricity demonstrate the greatest GCCP, significant since all three figure prominently within the current cooking fuel mix. Coal powder and sugarcane ethanol demonstrate the greatest CED, the former because of low stove thermal efficiency, and the latter because of energy loss in the supply chain.

Table 6-1. Summary Table of Single Fuel Results by Impact Category (Impact/GJ Delivered Cooking Energy) - China

Fuel Type	GCCP	CED	FDP	WDP	PMFP
	(kg CO_2 eq)	(MJ)	(kg oil eq)	(m^3)	(kg PM_{10} eq)
Coal Powder	1.16E+3	1.08E+4	254	1.15	21.5
Coal Briquettes	593	5.37E+3	125	0.986	0.989
Coal Honeycomb	527	6.37E+3	149	0.899	1.08
Firewood	190	7.61E+3	3.63E-3	4.00E-5	6.50
Crop Residue	64.1	7.45E+3	0.010	1.18E-4	10.0
Kerosene	225	3.53E+3	76.9	0.480	0.266
Biomass Pellets	140	3.78E+3	12.3	0.417	0.311
Electricity	612	7.22E+3	118	4.07	1.65
LPG	213	3.41E+3	74.4	0.461	0.248
Natural Gas	154	2.37E+3	55.3	0.025	0.048
Coal Gas	254	3.69E+3	82.3	0.576	0.495
Sugarcane Ethanol	113	1.31E+4	24.9	643	4.33
Biogas from Cattle Dung	11.4	4.06E+3	-	1.02	0.210

Table 6-1. Summary Table of Single Fuel Results by Impact Category (Impact/GJ Delivered Cooking Energy) - China

Fuel Type	POFP (kg NMVOC)	FEP (kg P eq)	TAP (kg SO_2 eq)	ODP (kg CFC -11 eq)	BC (kg BC eq)
Coal Powder	3.30	0.116	1.66	1.13E-7	4.45
Coal Briquettes	0.700	0.091	1.20	1.27E-7	0.105
Coal Honeycomb	1.82	0.084	1.05	1.15E-7	0.160
Firewood	2.23	4.50E-3	0.242	3.34E-11	1.42
Crop Residue	5.52	0.013	0.367	9.52E-11	2.20
Kerosene	0.582	0.013	0.960	1.85E-7	-0.032
Biomass Pellets	1.340	0.012	0.53	2.54E-8	0.031
Electricity	2.31	0.078	5.27	1.67E-7	-0.148
LPG	0.500	0.012	0.898	1.81E-7	-0.031
Natural Gas	0.181	6.80E-4	0.143	9.74E-7	-2.04E-3
Coal Gas	1.31	0.042	0.803	1.39E-5	0.038
Sugarcane Ethanol	0.511	0.039	4.33	2.75E-6	0.748
Biogas from Cattle Dung	0.114	-	0.106	-	0.035

6.1 Cooking Fuel Mix Scenario Results - China

Cooking fuel mix scenario results provide the most comprehensive perspective on the options for cookstove sector improvements included in the second phase of this project. Table 6-2 provides a guide to interpretation of bar axis labels.

Table 6-2. Cooking Fuel Mix Scenario Technology Options (*Figure Key*)

Fuel Mix Scenario Parameter Options	Description
Current Tech-Current Eff-Current Grid[1]	Assumes current stove technology, current average stove thermal efficiency values, and 2013 electrical grid mix.
Imp Tech-Current Eff-Current Grid	Assumes improved stove technology use, current average stove thermal efficiency values, and 2013 electrical grid mix.
Imp Tech-Imp Eff-Current Grid	Assumes improved stove technology use, improved stove thermal efficiency values, and 2013 electrical grid mix.
Imp Tech-Imp Eff-Clean Grid	Assumes improved stove technology use, improved stove thermal efficiency values, and the use of clean electricity in electric cookstoves.

[1] Tech = stove technology, Imp = improved, Eff = stove thermal efficiency

Figure 6-1 shows the effect of various model parameters on GCCP impact per GJ of cooking energy delivered for China. The baseline (current) cooking fuel mix yields approximately 420 kg of CO_2 equivalent emissions per GJ of cooking energy delivered.

Assuming constant use of stove technology and current stove thermal efficiencies, the BAU 2030 cooking fuel mix realizes only a seven percent reduction in GCCP. This cooking fuel mix assumes that relative reliance on coal reduces slightly, while the use of crop residue and firewood falls by over 50 percent to provide 11 percent of national cooking energy. LPG and coal gas use both increase in the BAU 2030 scenario. If improved stove technologies are adopted and stove thermal efficiencies improve for each fuel type within the scenario, the reduction in GCCP impact increases to nearly 26 percent below the current baseline cooking fuel mix impact. Overall, 58 percent of potential reductions, relative to the baseline, for the BAU 2030 scenario are attributable to stove technology and efficiency upgrades.

The Diverse Modern Fuel mix for China yields the greatest overall reduction in climate change impact. The cooking fuel mix alone realizes a 31 percent reduction in GCCP impact as compared to the baseline, which can be improved to 48 percent if stove technology and efficiency upgrades are achieved. Electric cookstoves are assumed to provide greater than 15 percent of cooking energy in three of the four future cooking fuel mix scenarios. In these scenarios, electric cookstoves are a significant contributor to GCCP, which makes the results sensitive to future changes in electrical grid mix. As an example, applying the assumption of a clean electricity grid to the Increased Electricity scenario improves GCCP impact reductions from 27 percent to 52 percent of the baseline impact.

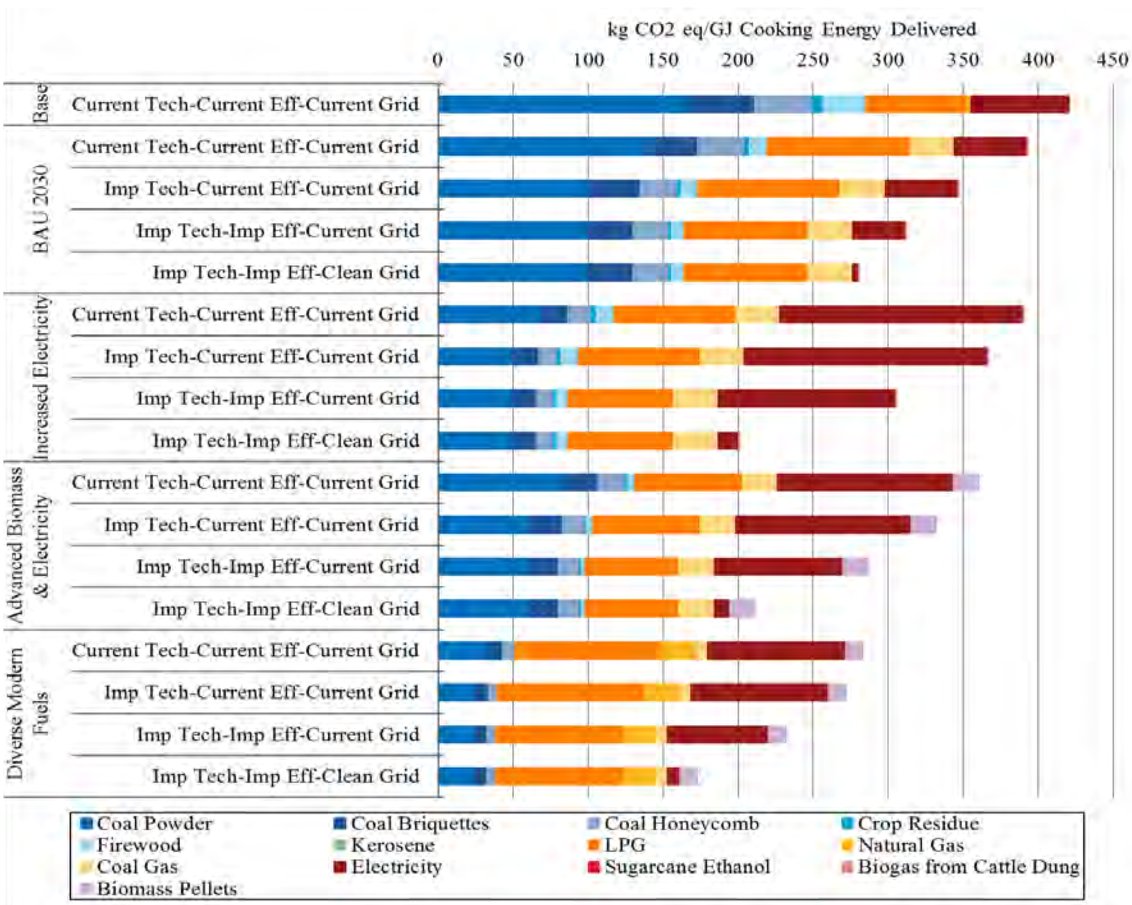


Figure 6-1. China GCCP cooking fuel mix scenario results.

(Axis abbreviations: Imp = improved, Tech = stove technology, Eff = stove efficiency)

Figure 6-2 demonstrates that reductions in PMFP are more sensitive to future cooking fuel mix upgrades than GCCP. PMFP impacts are also more sensitive, for a given cooking fuel mix, to stove technology and efficiency upgrades. Depending on the cooking fuel mix, stove technology and efficiency upgrades are able to reduce PMFP impacts by an additional four to 17 percent beyond those attributable to cooking fuel mix shifts alone. Cooking fuel mixes that rely more heavily on traditional coal and biomass fuels are the most sensitive to stove technology improvement. In the absence of stove technology and efficiency changes, reductions in PMFP impact between 31 and 81 percent are achievable through cooking fuel shifts alone. Movement away from the use of coal powder, firewood, and crop residue is responsible for most potential PMFP reductions. Even modest changes in the cooking fuel mix such as those represented by the BAU 2030 scenario can drastically reduce PMFP emissions.

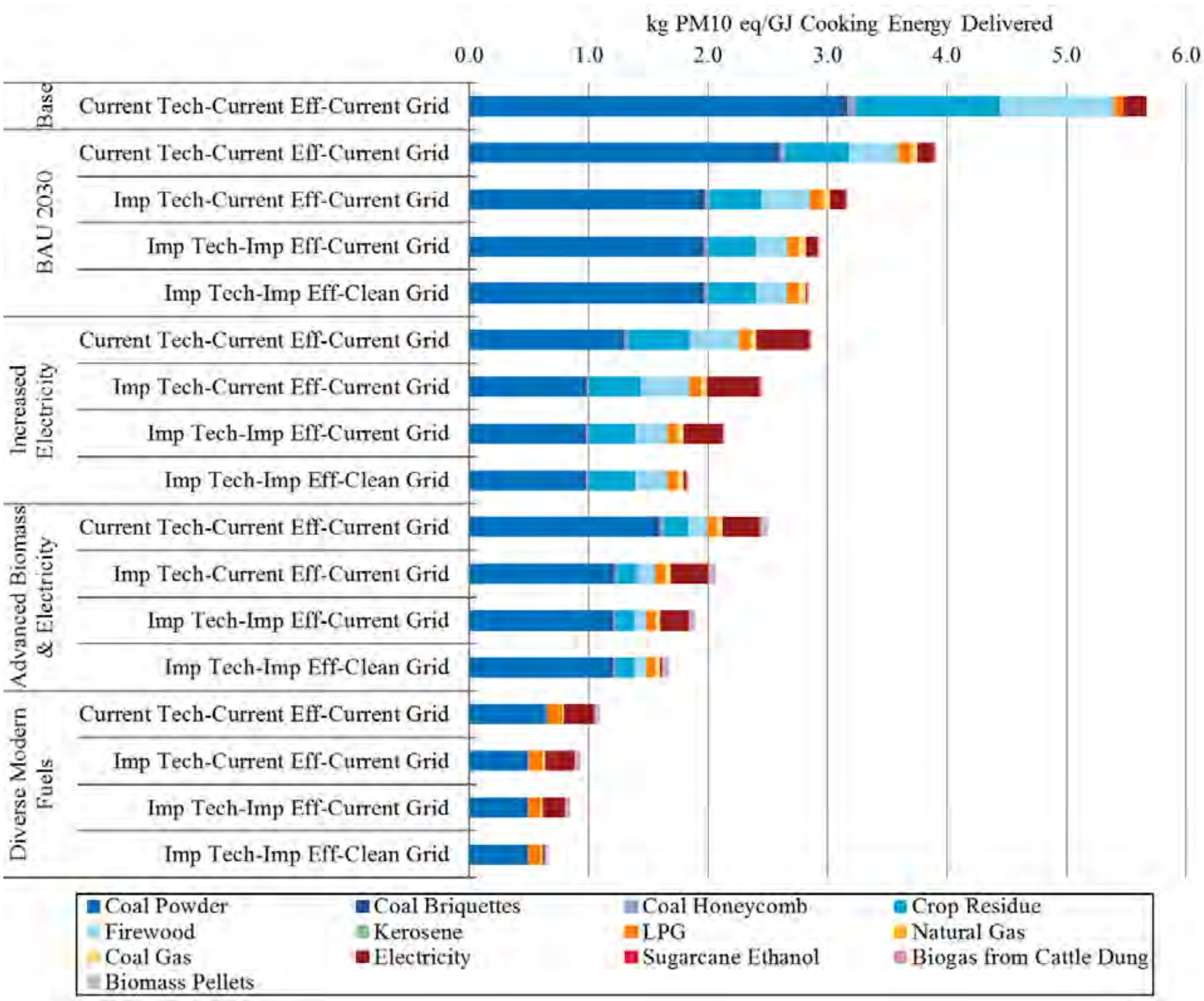


Figure 6-2. China PMFP cooking fuel mix results.

(Axis abbreviations: Imp = improved, Tech = stove technology, Eff = stove efficiency)

Figure 6-3 shows that adoption of the future cooking fuel mixes alone can reduce CED by between 15 and 34 percent. Lower CED is mostly attributable to reduced demand for coal powder, firewood, and crop residue, which have three of the four highest CED values of all the

Chinese cooking fuels included in this study. For the BAU 2030 and Increased Electricity cooking fuel mix scenarios, the additional adoption of improved stove technologies and increased thermal efficiencies can double the reductions possible through cooking fuel mix shifts to 34 and 32 percent, respectively. The Diverse Modern Fuels scenario holds the greatest potential for CED reduction, realizing a near 50 percent reduction in current energy demand per GJ of cooking energy assuming the adoption of improved stove technology.

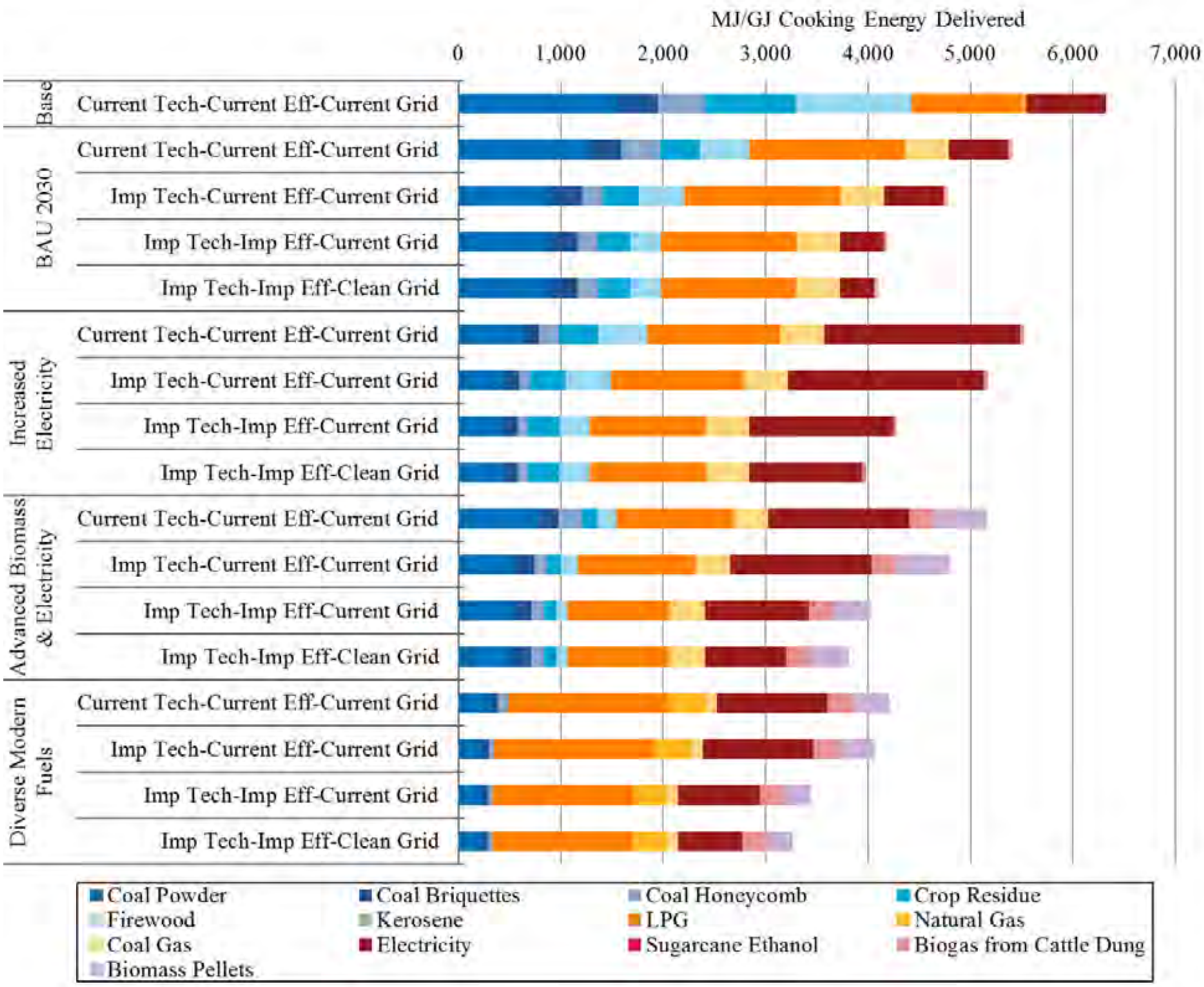


Figure 6-3. China CED cooking fuel mix results.

(Axis abbreviations: Imp = improved, Tech = stove technology, Eff = stove efficiency)

6.2 <u>Baseline Normalized Results - China</u>

The concept and methodology behind a normalized presentation of results is included in detail in Section 4.6. Generally, the results show which impact categories are most strongly linked to the activity studied. If normalization factors were perfectly calibrated, the sum of personal equivalent emissions for all sectors would equal the population of a given country, which for China is approximately 1.4 billion people. However, normalized emission estimates are uncertain due to lack of geographic granularity and the ever-changing nature of national or global level estimates for many categories, indicating that the relative magnitude of results and not the specific person equivalency value is of greater importance and validity. Normalized results indicate only the level of the cookstove sector contribution to the national economy-wide impacts; they do not imply that impact categories are of greater or lesser significance.

Figure 6-4 indicates that greater than 15 percent of national emissions contributing to PMFP, FEP, and BC are attributable to the cooking sector. PM and BC emissions in large part are produced by coal powder, firewood, and crop residue combustion. Other impact categories show a moderate link to the cooking sector with between five and ten percent of national emissions attributable to the cooking sector. WDP and ODP are the exception and do not appear to be significantly linked to the cooking sector in China. Normalized CED is lower for China than for other countries studied due to China's greater level of industrialization and higher energy demand per capita.

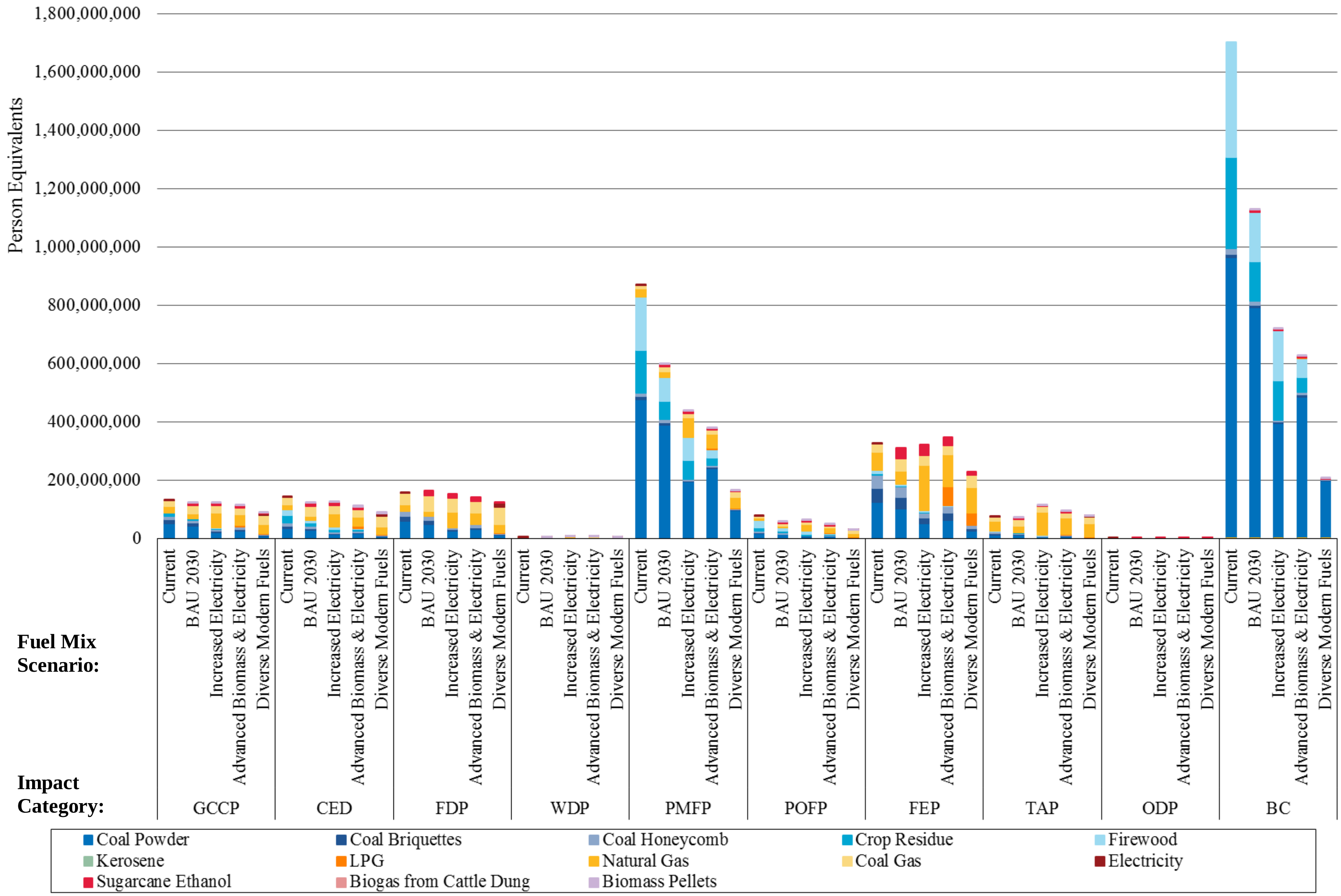


Figure 6-4. China normalized LCA results.

6.3 Stove Efficiency Sensitivity – China

Figure 6-5 presents GCCP for various coal-based cooking options in China. Each of the bars are labeled with the associated current or future improved stove thermal efficiency value for that stove group. Upstream energy losses, particularly associated with electricity production, are not included in these thermal efficiency values. The figure clearly shows the benefit of increased coal-based stove thermal efficiency in reducing climate impacts associated with cooking, even as the underlying feedstock remains the same or similar. The improvement demonstrated in the figure is not due solely to stove thermal efficiency, however, as fuel form also changes across the individual stove groups. The potential benefit of increasing stove thermal efficiency within a given stove group (e.g., coal powder, traditional) as opposed to adoption of improved stoves or fuel forms varies. The GCCP of coal powder-based cookstoves varies considerably from 840 to nearly 1400 kg CO_2 eq per GJ of delivered cooking energy. Overall, this range represents a nearly 40 percent potential reduction of GCCP impact when switching from traditional to improved coal powder stoves. The best performing traditional coal powder stoves can realize a 29 percent reduction in GCCP impact, relative to the current average stove thermal efficiency, for the same stove type. More advanced forms of coal fuel demonstrate less variation in stove thermal efficiency within a given stove group (e.g., honeycomb coal, improved) and upgrades in fuel form (e.g., from powder to honeycomb briquettes) present even more potential to mitigate impacts.

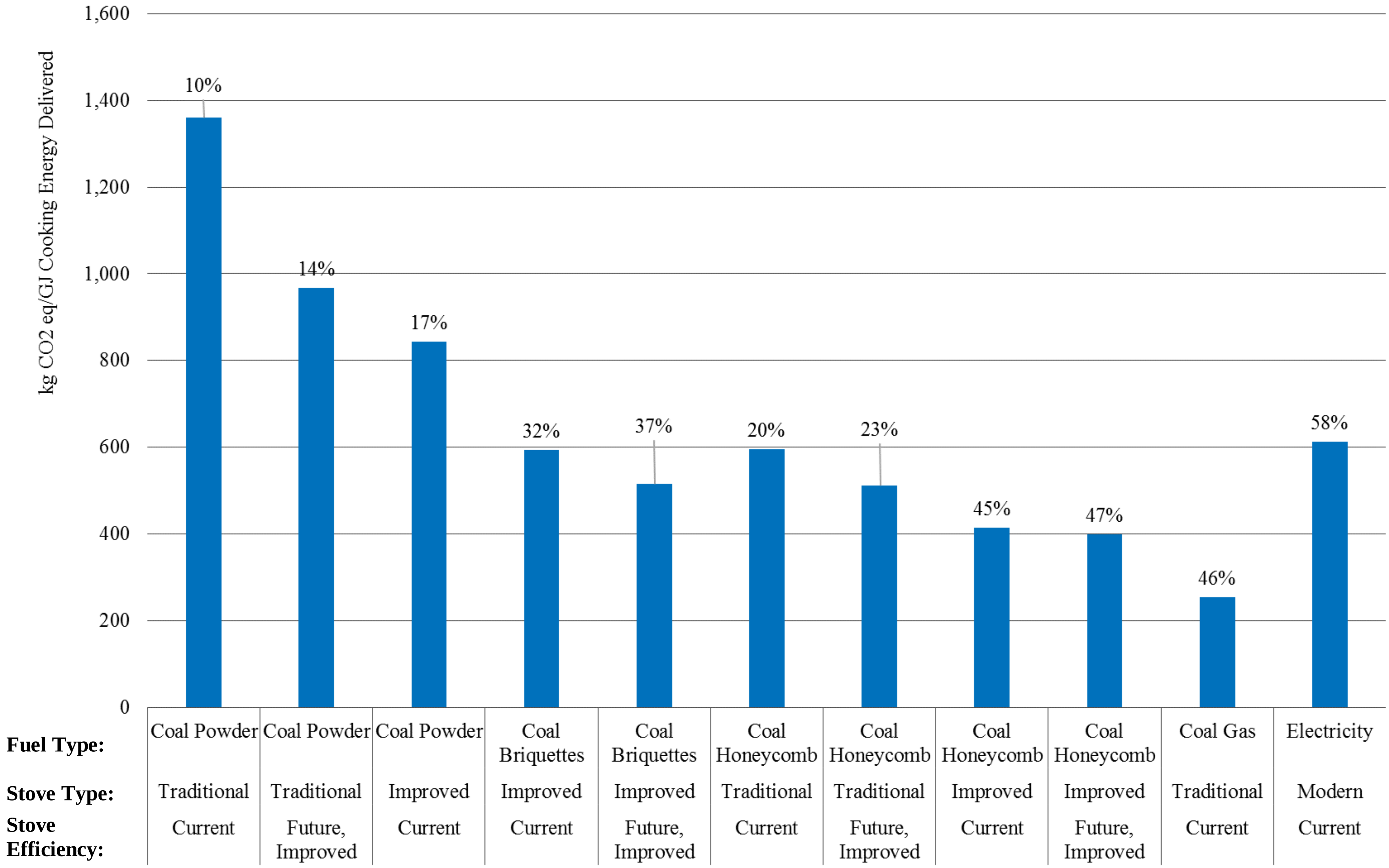


Figure 6-5. Cooking fuel form and stove thermal efficiency effects on GCCP of coal in China.

6.4 Electrical Grid Mix Results – China

Figure 6-6 shows that with the adoption of an improved electrical grid, it is possible to reduce climate change impacts associated with electric cookstove use by nearly 90 percent (LBNL AIS-2050 scenario). More modest interventions such as those represented by the LBNL CIS grid estimate for the year 2050 indicate a potential 43 percent reduction even in the absence of stove efficiency improvements. Reductions are attributable both to shifts in the electrical grid fuel mix and to the adoption of more advanced electricity generation technology that reduces fuel consumption per unit of delivered energy.

The best performing grids represent rapid departures from the current electricity fuel mix in China. The LBNL AIS 2050 scenario relies heavily on nuclear technology, while the IEA Blue Map scenario relies on an even mixture of renewables, gas, nuclear, and advanced coal technology. The affect that these improvements could have on the relative performance between electricity and other cooking fuels is an important consideration and can be explored in the results files for each country. While most impact categories follow a downward trend similar to that exhibited by climate change, ODP and BC impacts are two exceptions. ODP impacts tend to increase as more natural gas is included in the grid, while BC impacts increase as coal combustion is reduced. The high relative ODP of natural gas is due to emissions associated with long distance transport via pipeline. Sulfur dioxide emissions produced during coal combustion exhibit a short-term cooling effect, which account for the potential increase in BC impact as coal use drops.

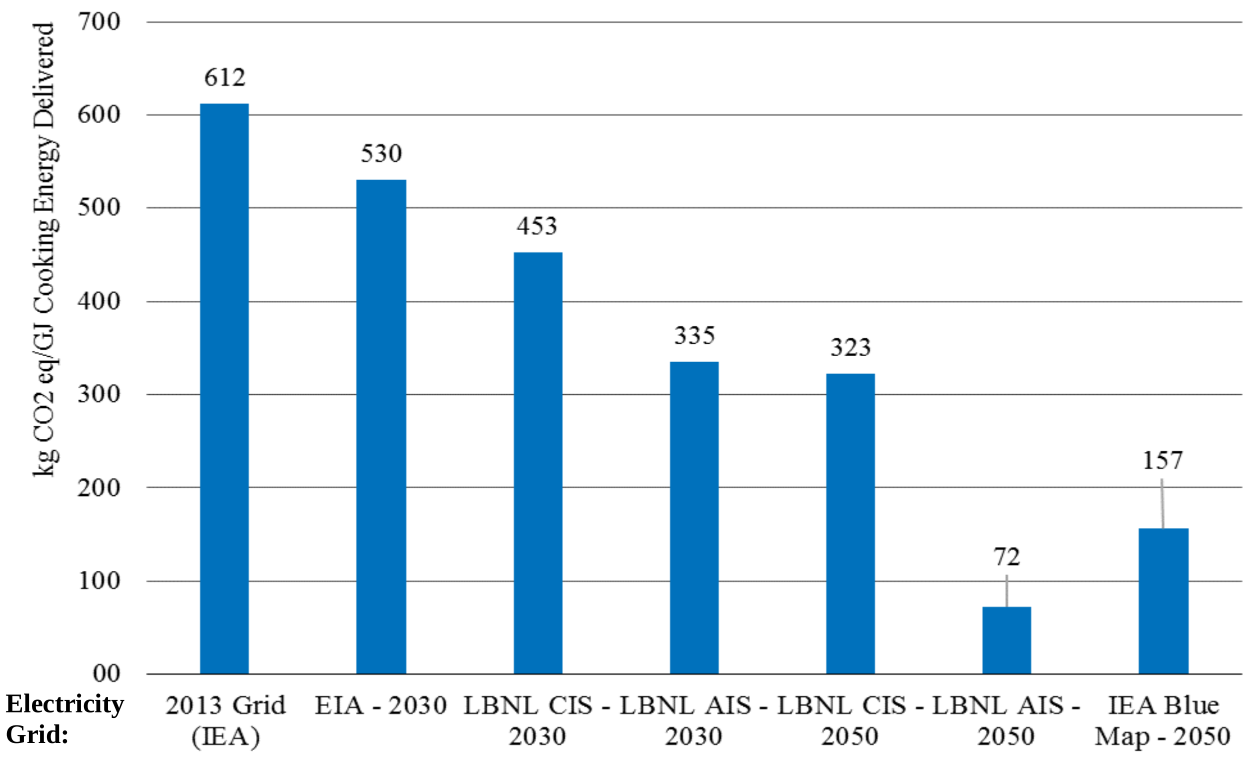


Figure 6-6. Effect of electrical grid mix on GCCP impact of electric cookstoves in China.

6.5 Forest Renewability Factor Sensitivity – China

The use of two separate methodologies to determine the fraction of forestry products that are renewably produced and are therefore carbon neutral leads to a 20 percent difference in the estimate of total forest products that are derived from sustainable operations. The assumptions behind these two methods were discussed previously in Section 4.2. The baseline values for Phase II of this study are from the WISDOM database (Drigo 2014) and lead to reductions in GCCP impact between 31 and 40 percent as compared to impacts associated with the low renewability factor used as the baseline in Phase I (Figure 6-7). The difference between the two forestry renewability factors affects the relative GCCP impact of the stoves depicted below and the modern liquid/gas fuels. In specific instances, the choice of renewability factor is enough to influence whether adoption of modern fuels yields an increase, decrease, or no significant effect on emissions contributing to climate change.

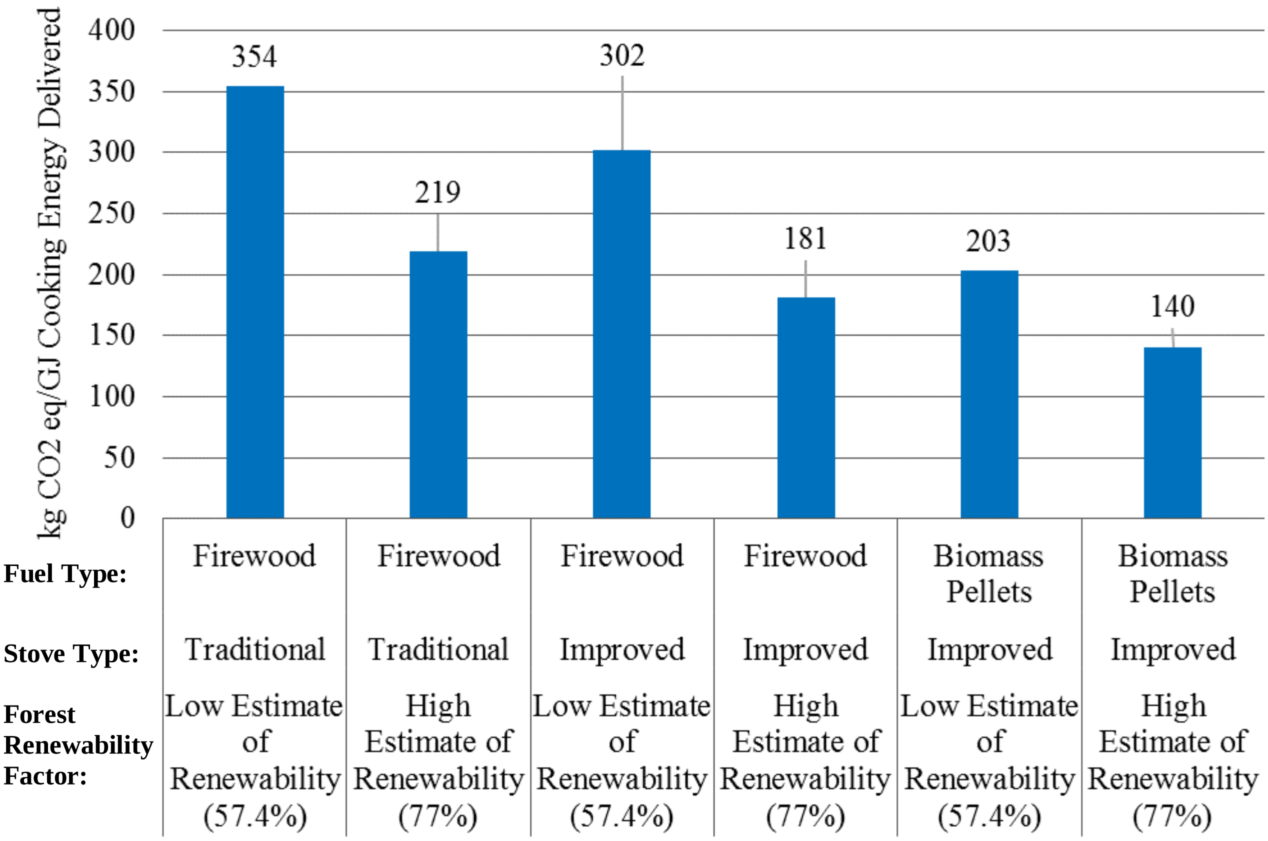


Figure 6-7. Comparative effect of forest product renewability assumption on GCCP in China.

6.6 Allocation Approach Sensitivity – China

This section describes the effects of LCA allocation modeling conventions on cookstove environmental impacts for crop residue, biogas, and sugarcane ethanol. For crop residue, the allocation issue centers on the question of how best to distribute environmental impact between food crops and other forms of agricultural biomass such as straw and stover. For biogas, the modeling question concerns how to allocate impacts of anaerobic digester operation between the biogas and the digestate. Sugarcane ethanol modeling questions concern both the agricultural impacts of sugarcane production and how best to deal with surplus co-produced electricity generated from bagasse during molasses and ethanol production.

Figure 6-8 (below) and Figure 6-9 demonstrate the effect of LCA allocation modeling choices on GCCP and PMFP impacts of stoves burning crop residue. When comparing the figures, it is clear that modeling choice has a variable effect depending upon the impact category being considered. GCCP impacts are not affected by the choice between a cutoff approach and system expansion, whereas the opposite is true for particulate emissions. The specific form of system expansion employed assumes that crop residue utilized in cookstoves avoids the field burning of those same residues. The biogenic origin of crop residues yields a limited climate impact, but the more controlled burning of crop residues in cookstoves produces a significant quantity of avoided particulate emissions from field burning. In general, GCCP is shown to increase if either physical or economic allocation is used to assign a portion of agricultural impacts to crop residue, and the specific type of crop modeled also influences GCCP results. PMFP shows a much lower sensitivity to the use of allocation and to the choice between physical or economic factors because the majority of PMFP impact is associated with the use phase when applying a cutoff, economic, or physical allocation approach. Fossil depletion, water depletion, eutrophication, acidification, and ozone depletion all show noticeable increases if a portion of agricultural impacts are allocated to the residue. Like PMFP, BC impacts are also strongly affected if the system expansion approach is used. Photochemical oxidant formation potential is not shown to be sensitive to any of the LCA modeling choices.

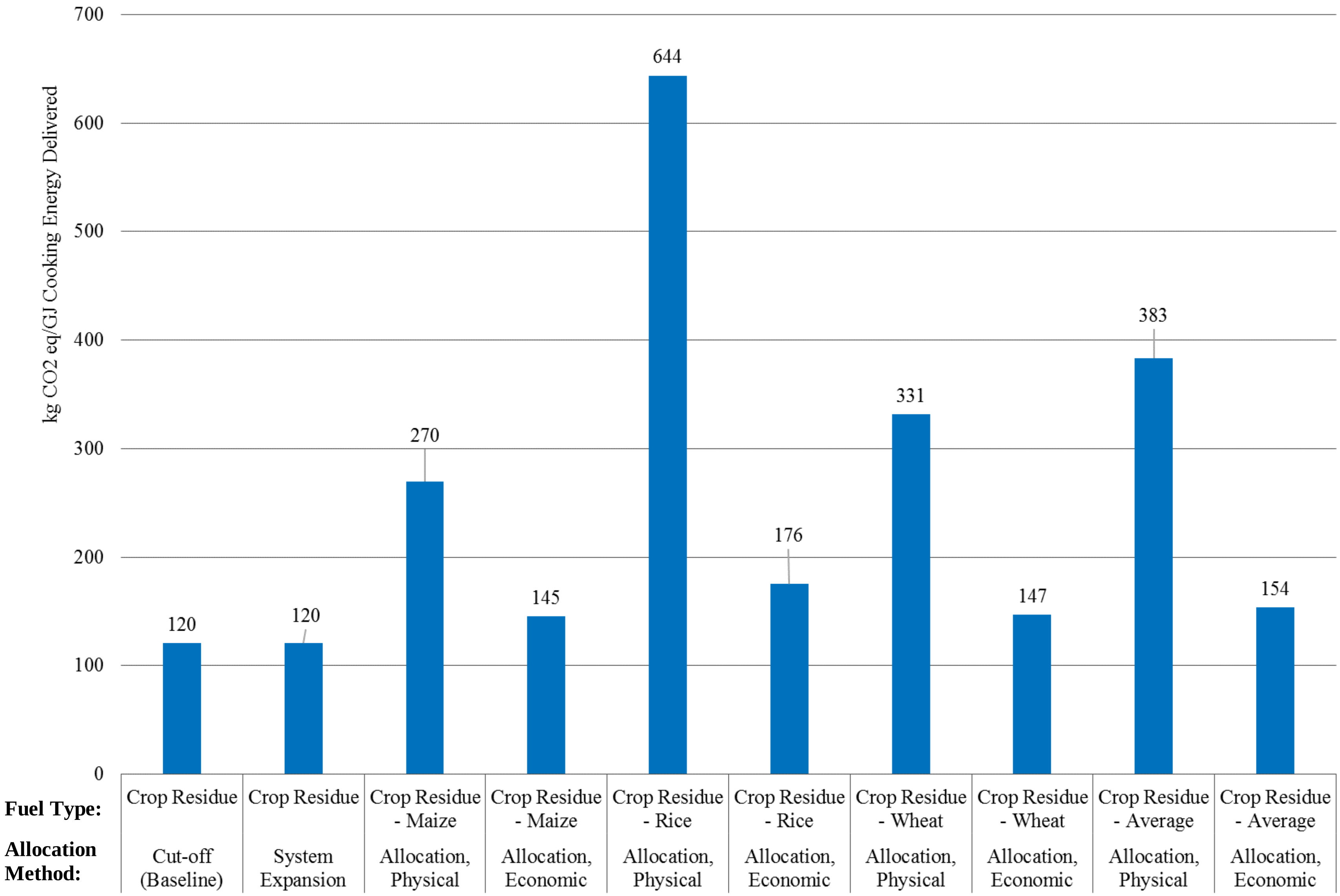


Figure 6-8. Effects of LCA allocation approach on crop residue GCCP impact in China.

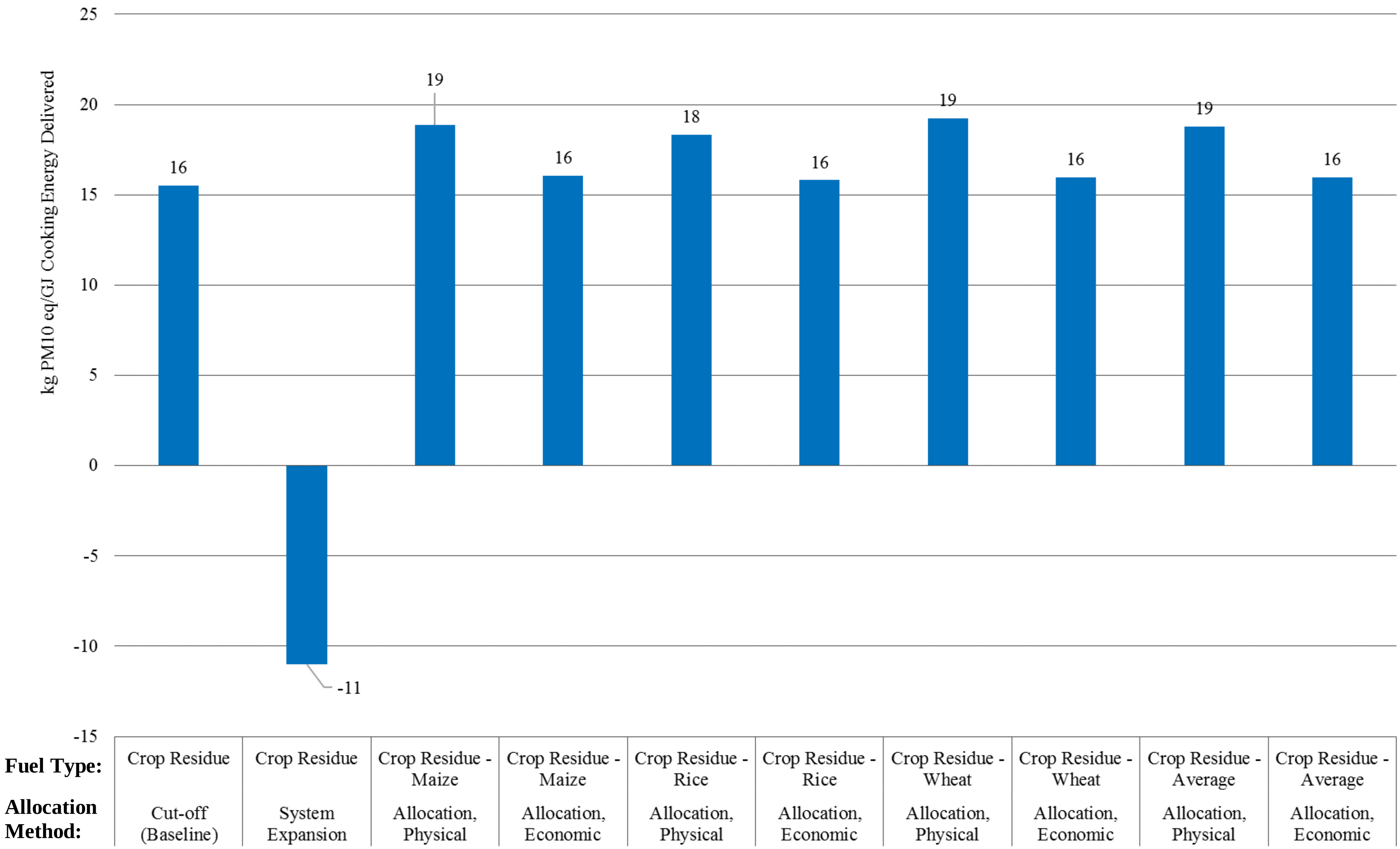


Figure 6-9. Effects of LCA allocation approach on crop residue PMFP impact in China.

Figure 6-10 shows that the TAP impact of biogas and sugarcane ethanol are sensitive to the system expansion approach, which is used to avoid allocating the burdens of multi-output processes. Acidification impacts associated with sugarcane ethanol are reduced as a result of the avoided electricity production generated because of bagasse combustion. Avoided electricity production also reduces environmental impacts for GCCP, FDP, POFP, and FEP between 60 and 160 percent, relative to the use of physical allocation. Results in other impact categories are less sensitive to this choice. The consideration of system expansion results for estimating the environmental impact of sugarcane ethanol use is justified for a number of reasons: (1) sugarcane is the main agricultural product and all LCA modeling approaches agree that it should be attributed a majority share of agricultural impacts, and (2) electricity production is a high value use of by-product bagasse, and the electricity is often used as a direct input within ethanol production and processing.

System expansion can be used to avoid the need to allocate impacts between biogas and the solid digestate that exit the digester. The approach credits both the environmental benefits and burdens of digestate land application to the biogas. For a number of impact categories like TAP, this approach leads to a marked increase in impacts associated with biogas. System expansion also leads to a greater than 30 percent decrease in GCCP, CED, WDP, and POFP impact. Environmental benefits realized are generally due to avoided fertilizer production, whereas increased environmental impacts are a result of emissions associated with the land application of digestate.

The system expansion approach is valid for biogas only if the digestion process impacts the decision to utilize the digestate as a fertilizer and soil amendment or if it has an impact on the quality of the product destined for use as an agricultural amendment. A review of the literature indicates a slight and somewhat variable impact of the digestion process on the fertilizer value of the digestate, when compared to the application of unprocessed manure. If this difference were more pronounced, then the net effect of the digestion process on avoided fertilizer production and agricultural emissions would be of greater importance to this analysis. In the absence of this observation, the cutoff approach is the more justifiable choice for modeling the environmental impacts of biogas production, which reinforces its choice as the baseline method for this analysis.

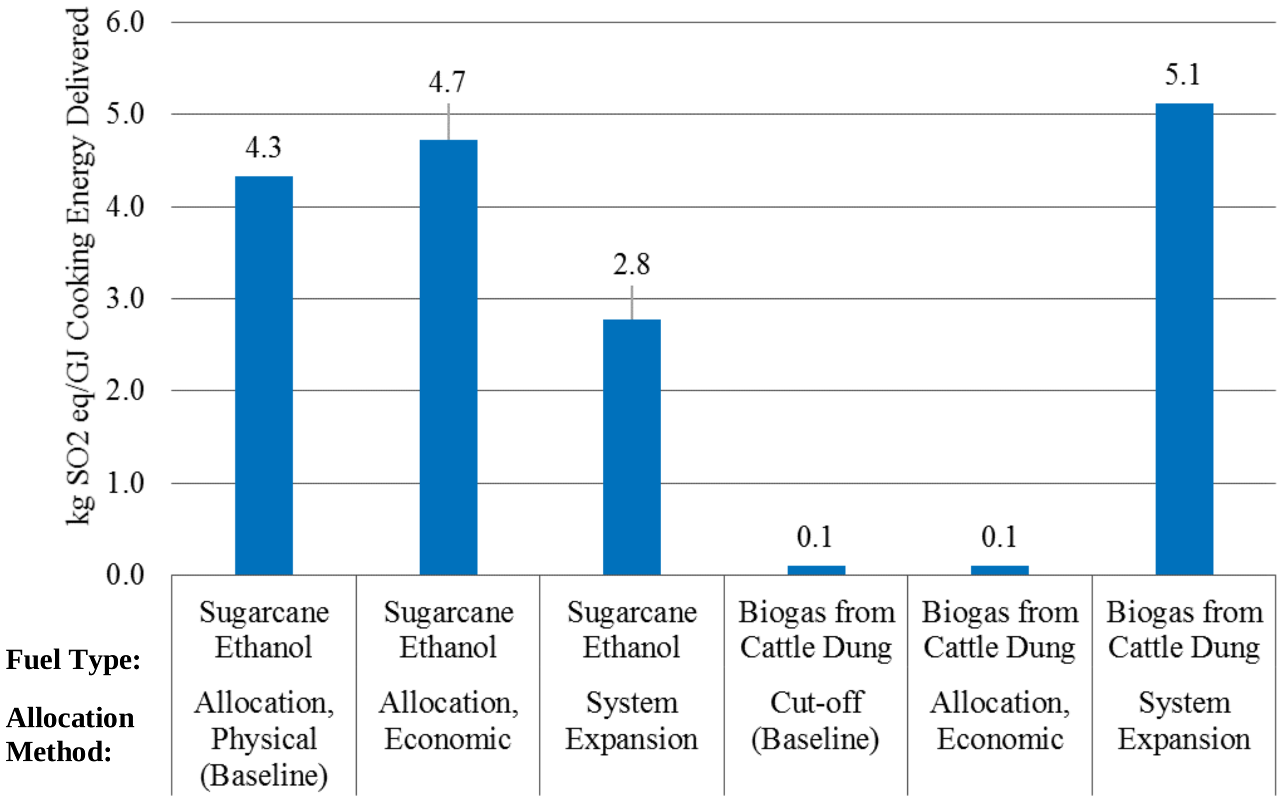


Figure 6-10. Effect of LCA allocation methodology on biogas and sugarcane ethanol TAP impact.

6.7 Stove Group Uncertainty Results - China

Figure 6-11 presents GCCP impact scores for improved and modern cookstoves. All results in the figure represent the baseline LCA allocation modeling convention. The height of the bar in each figure represents the Monte Carlo mean around which the error bars are centered. The analysis mean (triangle in figure) for each impact category is the characterized expected value as it was entered into openLCA. The analysis and Monte Carlo mean deviate from one another depending upon the distribution used, and in the case of lognormally distributed data, depending upon the geometric standard deviation.

The figure shows that despite some overlap in the uncertainty bands, real reductions in climate change impact are possible even within a given fuel type such as coal. Honeycomb coal briquettes and coal gas both represent improved forms of this fuel type that could present opportunities for GCCP reductions while still utilizing China's large coal resources. Burning coal in the electrical grid, as opposed to directly in cookstoves, does not appear to reduce GCCP significantly. The figure also shows that modern cooking fuels are not able to produce lower climate change impacts than traditional biomass fuels. Significant uncertainty exists concerning the carbon footprint of sugarcane ethanol, which is largely due to agricultural production of the sugarcane feedstock. The low climate impact of biogas use and production is supported by the uncertainty analysis.

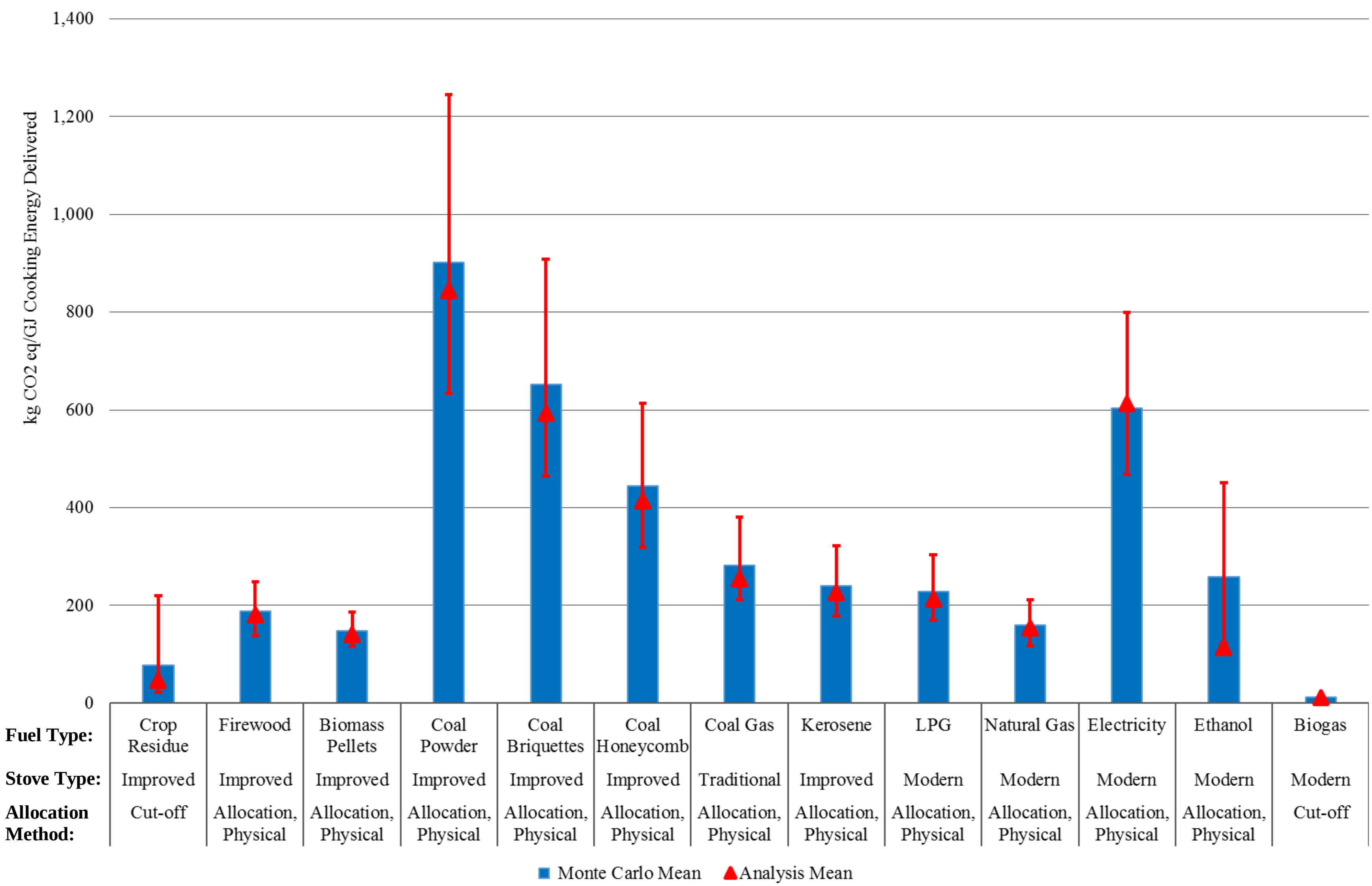


Figure 6-11. China GCCP uncertainty analysis results for improved stoves and modern cooking fuels modeled with various allocation approaches.

Figure 6-12 presents uncertainty ranges for PMFP impact scores for a wide range of cooking fuels and stove types. The uncertainty ranges associated with particulate emissions are generally wider than those for GCCP, which makes it difficult to distinguish differences between the stoves burning traditional fuels, based on results for this impact category. According to this figure, a strategy that promotes an upgrade from traditional to improved stove designs for the traditional fuels may not prove effective at reducing PM emissions in China. Improved forms of the traditional fuels such as honeycomb briquettes (coal) and biomass pellets (firewood) do realize significant reductions in PM emissions. From the perspective of PM emissions, the use of coal-based electricity as a cooking fuel yields emissions comparable to those possible with honeycomb briquettes. Modern liquid and gas fuels all yield significantly lower PM emissions than the traditional fuels when burned in either traditional or improved stove types.

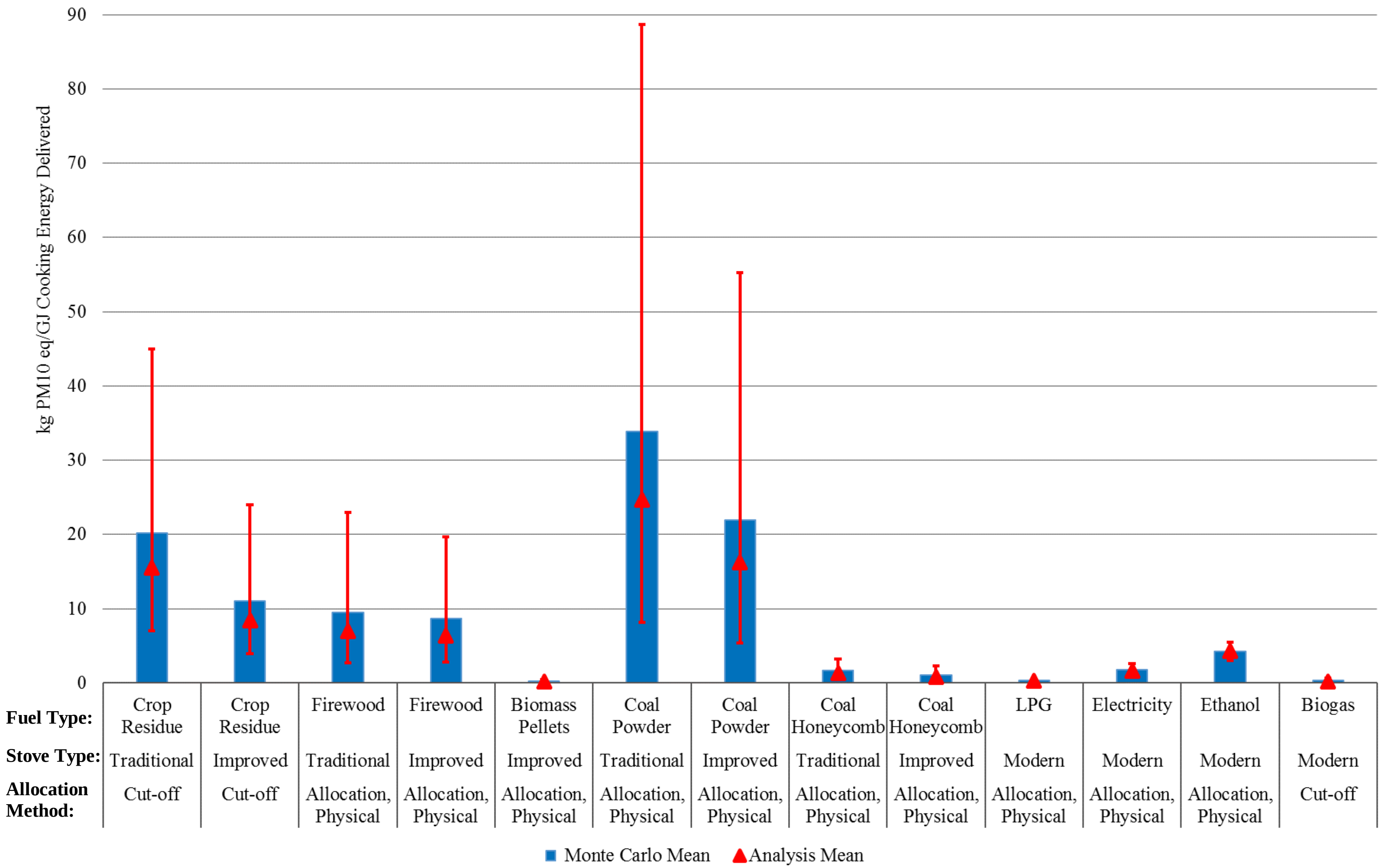


Figure 6-12. China PMFP uncertainty analysis results for select fuels modeled with various allocation approaches and stove technologies.

7. LCA RESULTS FOR KENYA

Sixty-five percent of Kenyan households rely on firewood for cooking energy (KNBS 2012), and the major portion of this fuel is still consumed in three-stone cookstoves (Githiomi et al. 2012, SEI 2016). Compared to other nations studied, Kenya is relatively early in the transition to the use of improved or modern fuels and stoves. Charcoal use is slowly on the rise and now comprises 17 percent of national cooking energy (CBS 2002, KNBS 2012). Kerosene use, currently providing less than 12 percent of cooking energy, appears to be beginning to fall in favor of modern fuels such as LPG (Dalberg 2013a). The results presented here explore how the environmental impact of the cooking sector will change if Kenya's cooking sector evolves similarly to the transition that has already been realized in Ghana, or if other pathways provide greater opportunities.

Table 7-1 presents summarized LCA results for all fuel types and impact categories in Kenya. The results are representative of baseline assumptions concerning cooking fuel mix, stove technology use, stove thermal efficiency, electricity grid, and forest renewability factor. Charcoal and firewood carry significantly greater GCCP impacts than do other cooking fuel options due to poor efficiency of current stove and kiln technologies and the high percentage of Kenyan forest products that are harvested using unsustainable practices. As with other nations, biogas and sugarcane ethanol demonstrate the lowest GCCP. Charcoal and ethanol demonstrate the highest CED due to energy losses during processing. Significantly greater processing energy losses are associated with African-produced fossil fuels than are reported for either India or China, leading to greater potential impacts across most of the reported categories. In Kenya, firewood produces more PM emissions than do charcoal stoves per GJ of delivered energy, due to the continued reliance on three stone fires. POFP of charcoal is double the POFP reported in India, attributable to higher reported values of NMVOC emissions at the kiln. PMFP of charcoal is roughly half of the PMFP observed in India, with the differences in reported kiln emissions responsible for the difference. Differences in the underlying electricity mix in each nation help to explain some of the difference in impact scores between countries. The Kenyan electricity mix demonstrates environmental impacts competitive with other modern fuels given that 66 percent of power is generated from hydroelectric and geothermal sources (IEA 2013c). The relative impact scores for other cooking fuel types and impact categories largely follow trends similar to those demonstrated by other nations investigated in this study.

Table 7-1. Summary Table of Single Cooking Fuel Results by Impact Category (Impact/GJ Delivered Cooking Energy) – Kenya

Fuel Type	GCCP	CED	FDP	WDP	PMFP
	(kg CO_2 eq)	(MJ)	(kg oil eq)	(m^3)	(kg PM_{10} eq)
Firewood	439	9.11E+3	7.20E-3	7.96E-5	15.5
Charcoal from Wood	808	1.22E+4	5.35	0.068	8.40
Biomass Pellets	261	4.21E+3	19.4	0.635	0.152
Kerosene	223	7.96E+3	186	0.856	0.202
LPG	216	7.51E+3	175	0.816	0.196
Electricity	238	7.40E+3	150	5.58	0.331

Table 7-1. Summary Table of Single Cooking Fuel Results by Impact Category (Impact/GJ Delivered Cooking Energy) – Kenya

Fuel Type	GCCP ($kg\ CO_2$ eq)	CED (MJ)	FDP (kg oil eq)	WDP (m^3)	PMFP ($kg\ PM_{10}$ eq)
Biogas from Cattle Dung	13.4	4.21E+3	-	3.29	0.187
Sugarcane Ethanol	90.0	1.31E+4	26.0	643	4.25
Fuel Type	**POFP (kg NMVOC)**	**FEP (kg P eq)**	**TAP ($kg\ SO_2$ eq)**	**ODP (kg CFC-11 eq)**	**BC (kg BC eq)**
Firewood	5.87	8.92E-3	0.226	6.62E-11	3.32
Charcoal from Wood	22.9	0.011	0.208	4.77E-8	2.03
Biomass Pellets	1.47	5.66E-3	0.186	2.31E-8	0.026
Kerosene	0.832	9.96E-3	0.540	1.30E-7	5.70E-4
LPG	0.783	0.011	0.524	1.48E-7	1.70E-4
Electricity	1.46	1.85E-3	1.17	3.08E-8	-0.032
Biogas from Cattle Dung	0.084	-	5.13E-3	-	0.040
Sugarcane Ethanol	0.431	0.034	4.08	2.74E-6	0.755

7.1 Cooking Fuel Mix Scenario Results – Kenya

Cooking fuel mix scenario results provide the most comprehensive perspective on the options for cookstove sector improvements included in the second phase of this project. Table 7-2 provides a guide to interpretation of bar axis labels.

Table 7-2. Cooking Fuel Mix Scenario Technology Options (*Figure Key*)

Fuel Mix Scenario Parameter Options	Description
Current Tech-Current Eff-Current Grid[1]	Assumes current stove technology, current average stove thermal efficiency values, and 2013 electrical grid mix.
Imp Tech-Current Eff-Current Grid	Assumes improved stove technology use, current average stove thermal efficiency values, and 2013 electrical grid mix.
Imp Tech-Imp Eff-Current Grid	Assumes improved stove technology use, improved stove thermal efficiency values, and 2013 electrical grid mix.
Imp Tech-Imp Eff-Clean Grid	Assumes improved stove technology use, improved stove thermal efficiency values, and the use of clean electricity in electric cookstoves.

[1] Tech = stove technology, Imp = improved, Eff = stove thermal efficiency

Figure 7-1 presents GCCP results for each cooking fuel mix scenario and the range of included stove technology options. Results for the BAU 2030 scenario represent only marginal changes relative to the current cooking fuel mix and yield roughly equivalent results, although the attribution to individual cooking fuel types changes slightly. Assuming improved stove technology use for the BAU 2030 fuel mix holds the potential to reduce GCCP impact by approximately 32 percent. If improvements in the thermal efficiency for each stove type are also adopted, this reduction can be increased to 44 percent relative to the baseline. Limited electricity use is assumed in all but the Diverse Modern Fuels mix, which explains the limited sensitivity of fuel mix results to the possible adoption of a cleaner electricity grid.

In the Ghana Transition (for Kenya) scenario, an increased reliance on Charcoal and LPG to provide 27 and 24 percent of national cooking energy, respectively, leads to a slight increase in GCCP impact per GJ of delivered cooking energy. Adoption of improved stove and kiln technology helps realize a 27 percent reduction in GCCP impact primarily by reducing the impact associated with firewood and charcoal use and production. Targeting improvements in stove thermal efficiencies facilitates an additional 11 percent reduction in GCCP. The Slow Transition scenario produces impacts similar to the Ghana Transition (for Kenya) scenario, but a larger fraction of impact is attributable to firewood as opposed to LPG and charcoal.

The Diverse Modern Fuels scenario realizes a 25 percent reduction in GCCP impact based on changes in the cooking fuel mix alone. The adoption of improved stove technology and advancements in stove thermal efficiency demonstrate a smaller relative effect on this fuel scenario because the current efficiency of modern stoves tends to be much closer to the future improved efficiency than is the case for traditional fuels. In other words, the benefits of increased thermal efficiency are already being considered within the current scenario assumptions for stove technology and thermal efficiency for the modern fuel options. The introduction of a clean electricity grid leads to a modest, but noticeable, reduction in GCCP impact of approximately three percent. The maximum GCCP reduction calculated for the Diverse Modern Fuel Scenario is 51 percent, relative to the baseline.

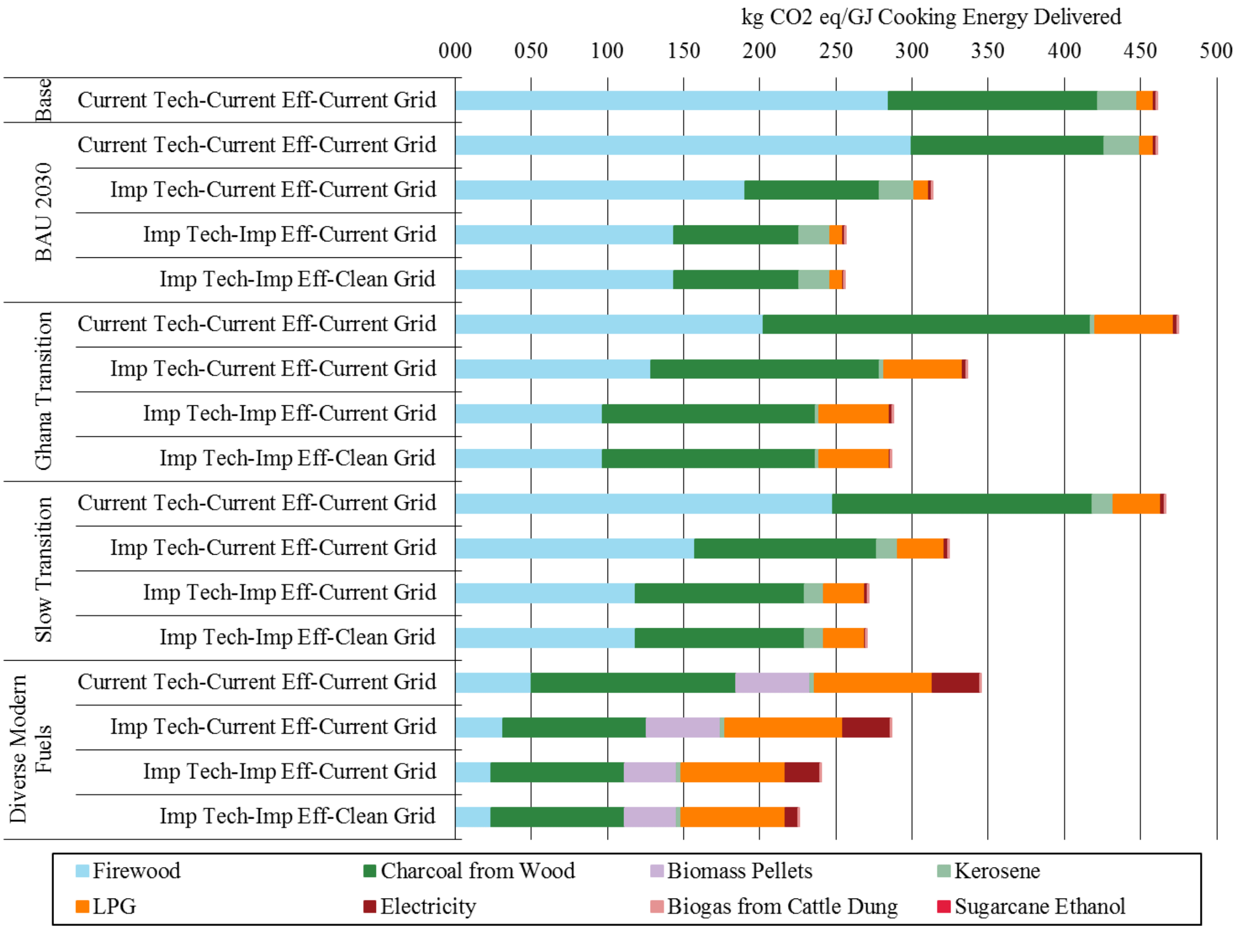


Figure 7-1. Kenya GCCP cooking fuel mix scenario results.

(Axis abbreviations: Imp = improved, Tech = stove technology, Eff = stove efficiency)

Figure 7-2 indicates that CED follows roughly the same general pattern as the results discussed above for GCCP. A close inspection of the values indicates that CED reductions associated with the Ghana and Slow Transition scenarios are a few percentage points higher than the values quoted for GCCP. For the Diverse Modern Fuels scenario, the CED reductions are a few percentage points lower than those quoted above for GCCP. The consistency in results between GCCP and CED that is present here is not necessarily an intrinsic one. Looking at the figure, we can see that LPG contributes a greater share of CED, whereas charcoal contributes a greater share of GCCP. It just so happens that in this case, the differences in contribution between fuels largely cancel each other out.

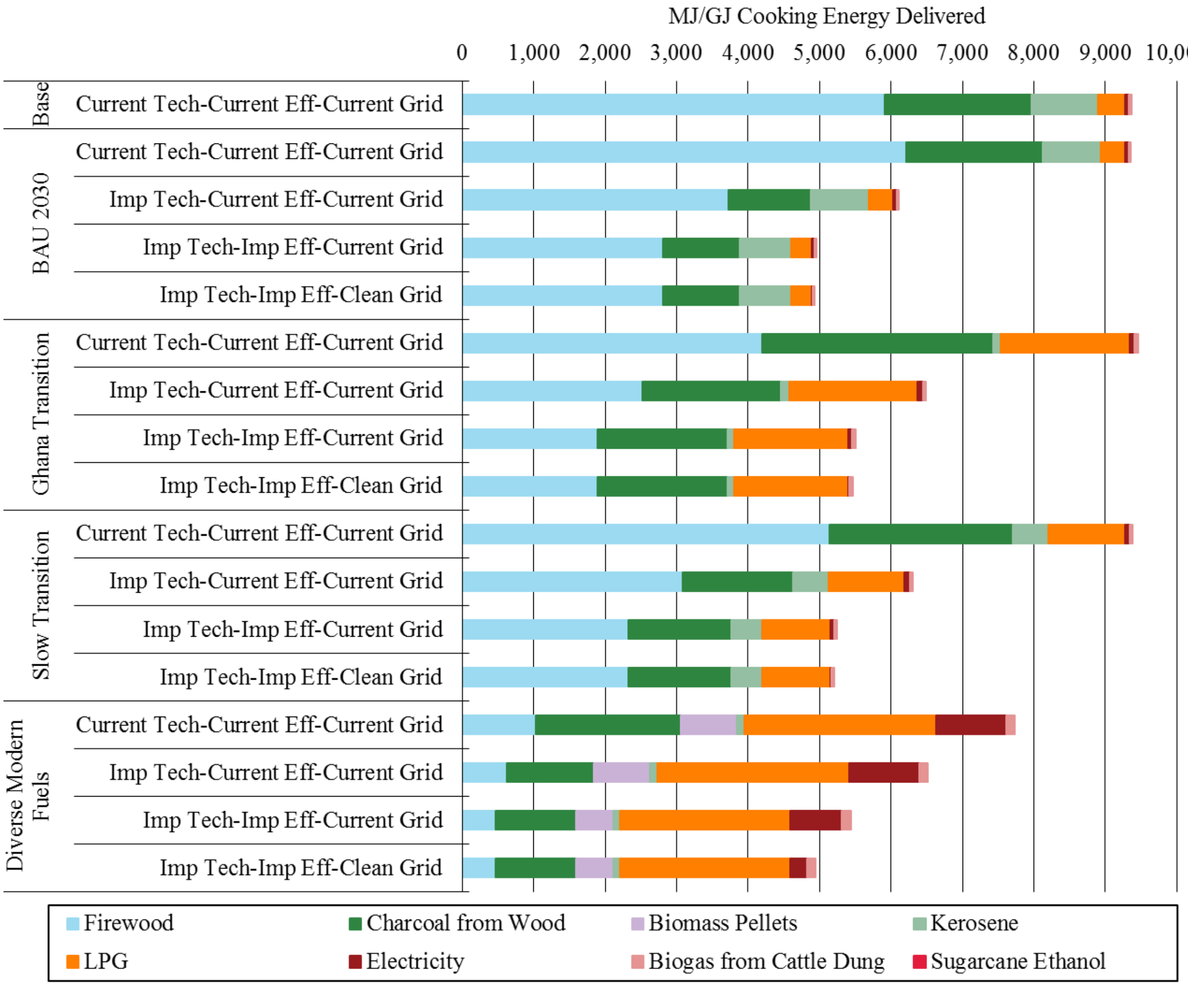


Figure 7-2. Kenya CED cooking fuel mix scenario results.

(Axis abbreviations: Imp = improved, Tech = stove technology, Eff = stove efficiency)

Figure 7-3 shows that PMFP impacts are not particularly sensitive to the BAU 2030, Ghana Transition (for Kenya), and Slow Transition Fuel mix scenarios in the absence of assumed technology improvements. This lack of sensitivity is attributable to the fact that substituting charcoal for firewood has a more limited effect on PMFP emissions as compared to other possible substitutions, due to the emission of PM at the kiln. Increases in LPG use translate directly into reductions in relevant particulate emissions. The ability to achieve PMFP reductions responds more positively to technology improvements. The adoption of improved stove technology for the BAU 2030 fuel mix scenario leads to a 69 percent reduction in PMFP. Assuming both improved stove technology and thermal efficiency values under the Ghana Transition (for Kenya) fuel mix yields a PMFP reduction of 77 percent. Using the same technology assumptions for the Diverse Modern Fuels scenario reduces PMFP impact by nearly 90 percent relative to the baseline. The introduction of a clean grid has very little effect on PMFP impact even for the Diverse Modern Fuels scenario, in which it comprises 13 percent of the cooking fuel mix, due to low PMFP impact of both current and potential electricity grids.

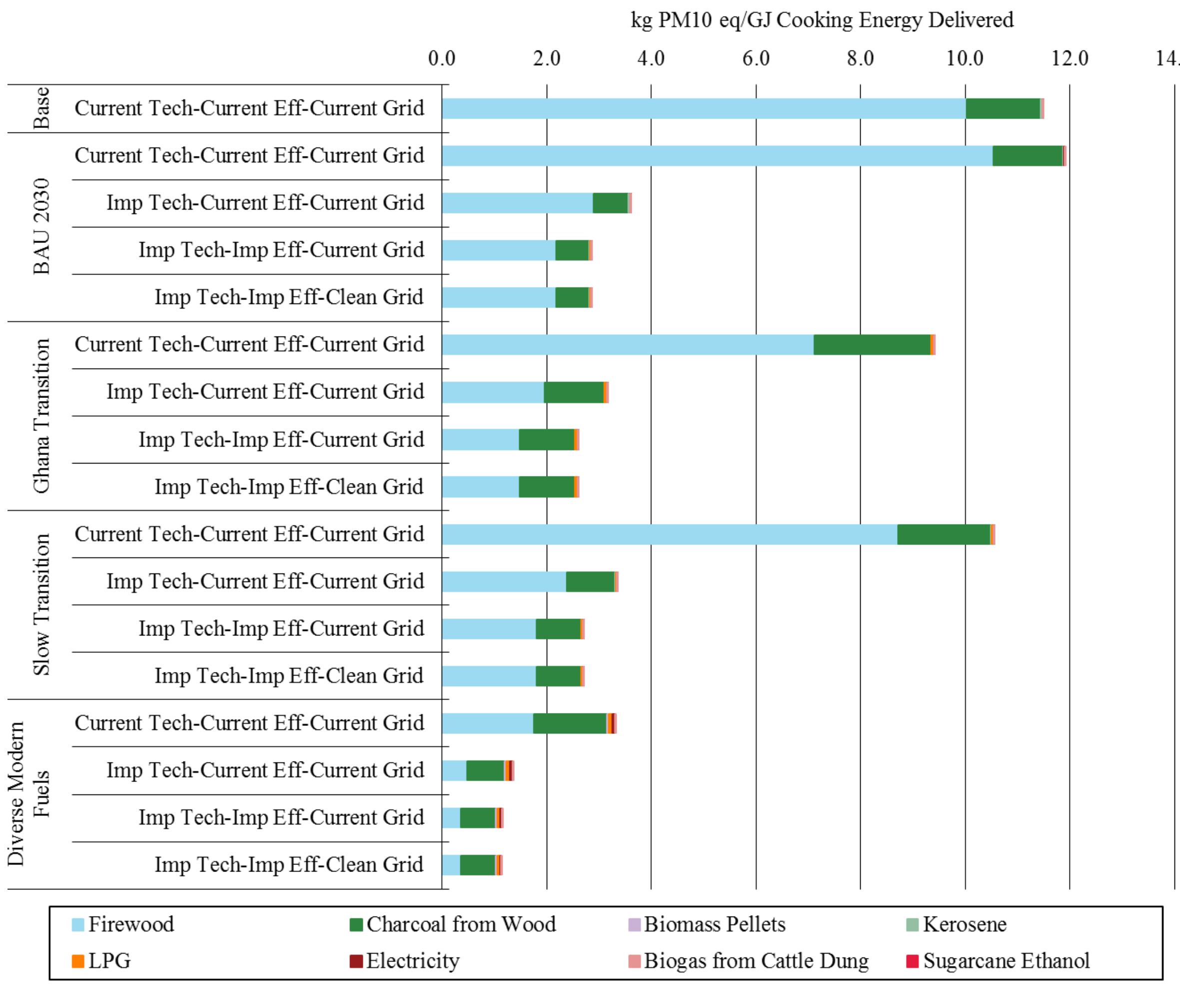


Figure 7-3. Kenya PMFP cooking fuel mix scenario results.

(Axis abbreviations: Imp = improved, Tech = stove technology, Eff = stove efficiency)

7.2 Baseline Normalized Results – Kenya

The concept and methodology behind a normalized presentation of results is included in detail in Section 4.6. Generally, normalized results show which impact categories are most strongly linked to the activity studied. If normalization factors were perfectly calibrated, the sum of personal equivalent emissions for all sectors would equal the population of a given country, which for Kenya is approximately 44 million people. However, normalized emission estimates are uncertain due to lack of geographic granularity and the ever-changing nature of national or global level estimates for many categories, indicating that the relative magnitude of results and not the specific person equivalency value is of greater importance and validity. Normalized results indicate only the level of the cookstove sector contribution to national economy-wide impacts, they do not imply that impact categories are of greater or lesser significance.

Normalized results for Kenya, presented in Figure 7-4, indicate that the cooking sector contributes significantly to national energy demand and emissions responsible for PMFP, POFP, and BC impact. As with India and China, the normalized impacts for Kenya are highest for BC and PMFP, in part due to the incomplete inventory of BC pollutant emissions that are accounted for in the normalization factor, and also due to the presence of negative characterization factors within the method which allows for BC impacts greater than 100 percent of net national impact. Regardless of the specific values, the results indicate that cookstove use is a dominant contributor to BC impacts. Normalized impacts for POFP are noticeably higher in Kenya than they are for India and China, which is largely due to the use of charcoal. Normalized CED results indicate that approximately 43 percent of national energy demand in Kenya is attributable to the cooking sector, which is higher than that realized for both India and China, and is attributable to lower per capita energy demand in Kenya. Normalized results associated with GCCP indicate that approximately seven percent of national GHG emissions are associated with household cooking within the current fuel mix scenario. Other impact categories do not appear to be particularly dependent upon the current cooking sector.

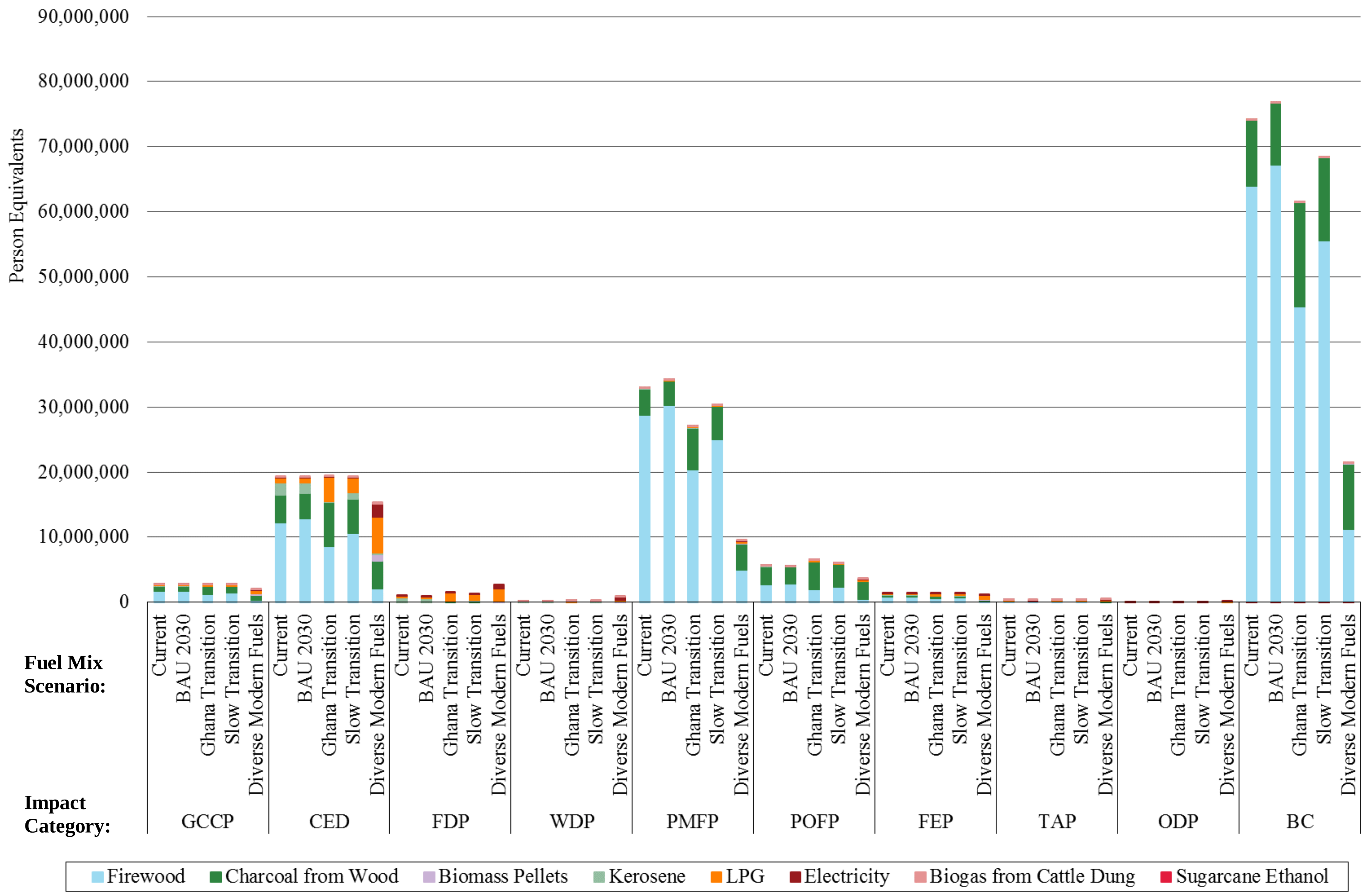


Figure 7-4. Kenya normalized LCA results.

7.3 Stove Efficiency Sensitivity – Kenya

Figure 7-5 shows the PMFP of wood-based stove groupings, highlighting the potential reductions in particulate emissions attributable to stove and kiln efficiency improvements. Each of the bars is labeled with the associated current or future improved stove thermal efficiency value for that stove group. The figure indicates that thermal efficiency is an important indicator of PMFP emissions within a given fuel type. The potential PMFP reductions evident in this figure are heightened by the knowledge that cookstoves make a significant contribution to national PM emissions as is indicated by the normalized results, and also that over 50 percent of households still burn solid wood fuel in a three-stone fire. An over 99 percent reduction in PMFP emissions is possible if pelletized biomass is adopted as a replacement for three-stone fires. Charcoal cookstoves have a lower potential to achieve reduced PMFP emissions as compared to non-carbonized solid woodfuel due to kiln emissions. Still, a 65 percent reduction in charcoal cooking emissions is possible if improved charcoal stoves burning fuel from a high-performing kiln are substituted for traditional cookstoves burning charcoal from an average kiln, the latter of which constitutes 45 percent of charcoal usage in Kenya today (Clough 2012).

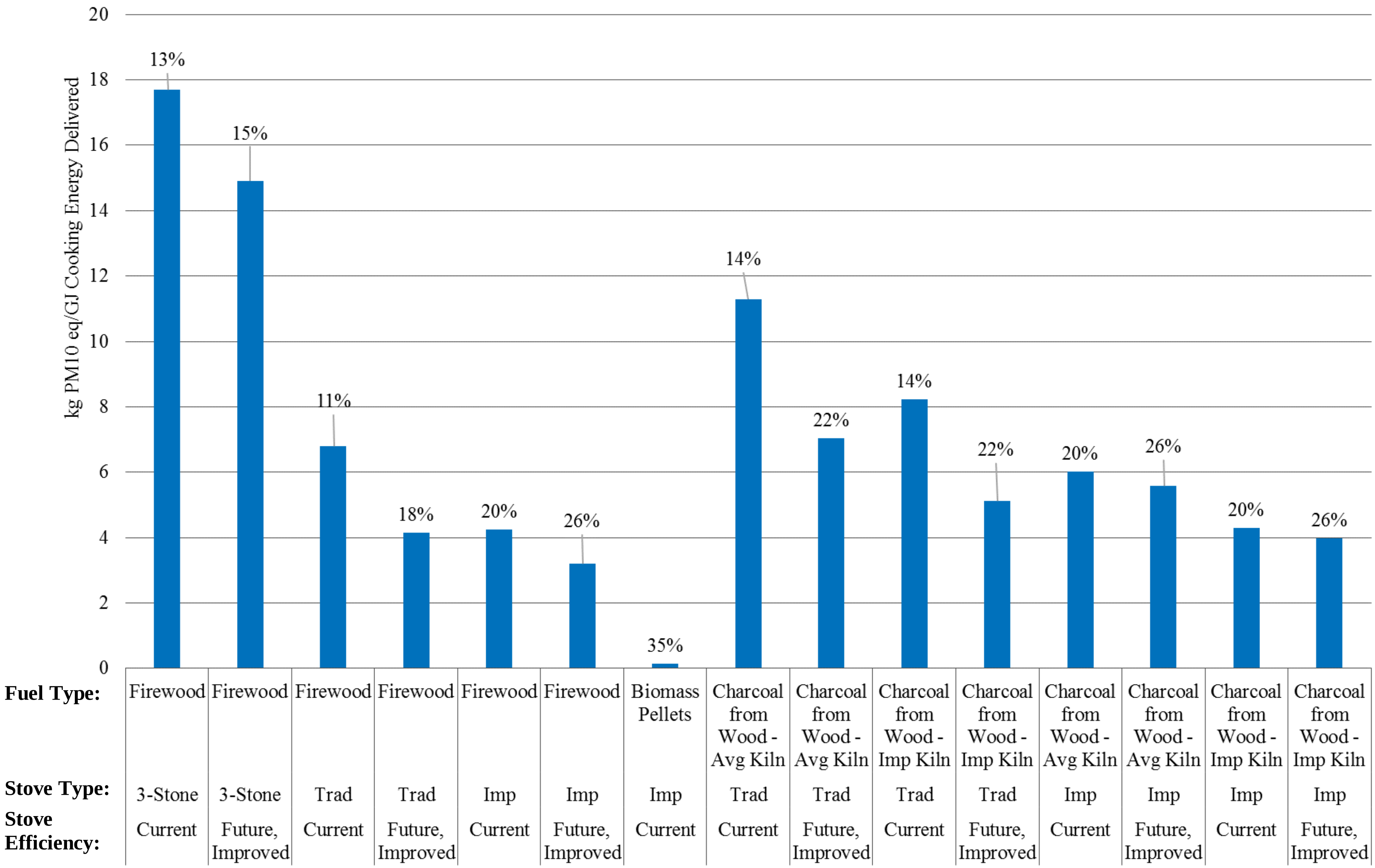


Figure 7-5. Kenya PMFP effect of stove thermal efficiency modeled with various stove technologies. (Axis abbreviations: Imp = improved, Trad = traditional, Avg = average)

7.4 Electricity Grid Mix Sensitivity – Kenya

The current electrical grid mix in Kenya is predominantly fueled by hydropower, oil, and geothermal energy. All future grid projections, which are forced to tackle the challenge of rapidly increasing consumer demand, indicate reliance on a greater diversity of fuel types, which include nuclear, coal, natural gas, wind, and solar. Figure 7-6 shows that the majority of future grid mixes have the potential to significantly reduce the carbon footprint of electric cookstoves that utilize their power. The McKinsey grid, however, would yield a negligible change in the carbon footprint of electric stoves, owing to a dramatic increase in reliance on fossil fuels as compared to the current grid mix. Even the current Kenyan grid mix provides a relatively clean source of cooking energy, producing just 240 kg of CO_2 equivalent emissions per GJ of delivered cooking energy in comparison to over 450 kg for both India and China. If any of the four cleanest electrical grid mix projections can be realized, electricity as a source of cooking energy will have the optimal climate performance of all the cooking fuels studied, with the exception of biogas and potentially sugarcane ethanol, depending upon where its true GCCP lands within the calculated uncertainty range.

Results in all other impact categories, with the exception of FEP and BC, decrease for all electric cookstoves relying on any of the projected future grid mixes, taking the 2013 grid mix as baseline.

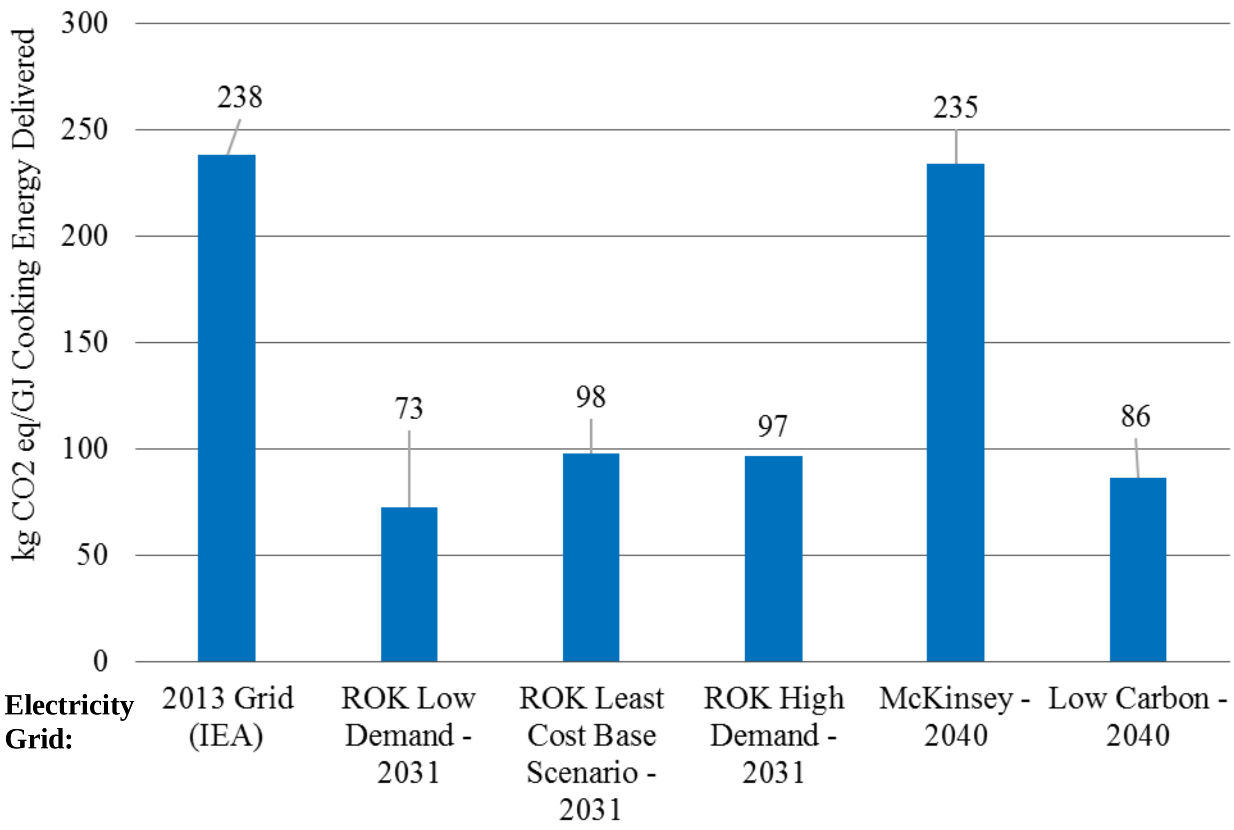


Figure 7-6. GCCP of electric cookstove with various electrical grid mix options in Kenya.

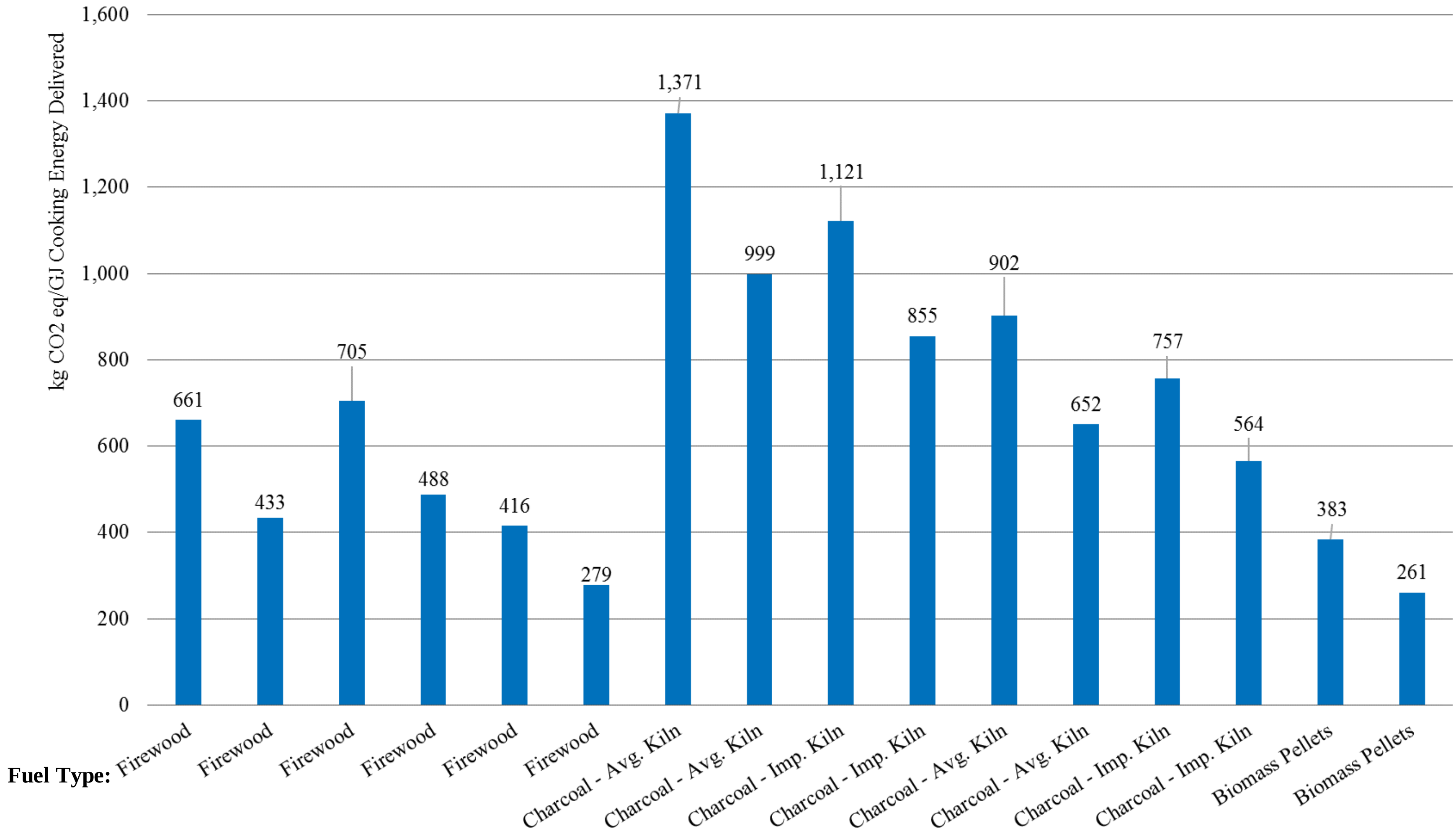
7.5 Forest Renewability Factor Sensitivity – Kenya

Figure 7-7 shows the effect of forest renewability factors on the GCCP impact of wood-based fuels produced and consumed in Kenya. Kenya has the highest percentage of forestry operations that are considered to be non-renewable of the four nations studied. The estimate based on the WISDOM database (Drigo 2014) indicates that only 36 percent of forestry products are currently produced via sustainable operations. This scenario is labeled as the high renewability (high renew.) option in the figure and is taken as the baseline for Phase II of this study. A method previously used to determine forest renewability factors indicated that 100 percent of forest land is managed unsustainably, and therefore emissions associated with wood combustion are not considered to be carbon neutral (low renew.). The assumptions behind these two methods were discussed previously in Section 4.2.

The choice between forest renewability factors yields a 24 to 42 percent difference in impact scores depending upon fuel and stove type. Solid firewood options are slightly more sensitive to the choice of renewability factor than is charcoal, likely owing to greater GCCP contributions for charcoal that are not related to the affected carbon dioxide emissions (e.g., CH_4). The figure also clearly shows that while the choice of renewability factor is important, there are other decisions such as fuel form and stove/kiln efficiency that have a greater impact on GCCP impacts per GJ of delivered heat.

Forest renewability factor is incredibly important in the determination of whether even the best performing wood-based options, biomass pellets and improved firewood stoves, are able to compete with the GCCP of modern liquid and gas fuel options. Given the uncertainty ranges for each fuel and assuming the high renewability factor, the use of firewood in improved stoves has a climate impact which is roughly equivalent to the modern fossil fuels. If the low renewability factor is applied, then the climate impact of firewood combustion in improved stoves exceeds that of all the modern fuel options.

Forest renewability factors are based on current estimates regarding the sustainability of forestry operations. If significant efforts are made to improve the efficiency of firewood use, for example through the widespread adoption of pelletized wood stoves, then the renewability factor could improve over time. General improvements in forestry practices, such as increased effort to replant following harvest, could also improve the sustainability of national forestry operations. Alternatively, increased consumer demand for wood products without the adoption of improved practices will surely cause the sustainability of national forestry operations to deteriorate.



Stove Type:	3-Stone	3-Stone	Trad	Trad	Imp	Imp	Trad	Trad	Trad	Trad	Imp	Imp	Imp	Imp	Imp	Imp
Forest Renewability Factor:	Low Renew.	High Renew.	Low Renew.	High Renew.	Low Renew.	High Renew.	Low Renew.	High Renew.	Low Renew.	High Renew.	Low Renew.	High Renew.	Low Renew.	High Renew.	Low Renew.	High Renew.

Figure 7-7. Comparative effect of forest product renewability on GCCP in Kenya modeled for various stove technologies.

(Axis abbreviations: Imp = improved, Trad = traditional, Renew. = renewability)

7.6 Stove Group Uncertainty Results – Kenya

Uncertainty results for stoves burning different forms of wood-based fuel are presented for both GCCP and PMFP in Figure 7-8 and Figure 7-9, respectively. All results in the figures represent the baseline LCA modeling convention. The height of the bar in each figure represents the Monte Carlo mean around which the error bars are centered. The analysis mean (triangle in figure) for each impact category is the characterized expected value as it was entered into openLCA. The analysis and Monte Carlo mean deviate from one another depending upon the distribution used, and in the case of lognormally distributed data, depending upon the geometric standard deviation.

GCCP of charcoal stoves is significantly greater than GCCP of firewood stoves due to inefficient wood and energy conversion at the kiln. Particularly noticeable in the figure is that almost no overlap in uncertainty ranges exists between any of the firewood and charcoal stove options for GCCP. However, differences within a fuel type tend to be obscured by overlap in the uncertainty ranges. Despite the overlap, it seems reasonable to assume that real reductions in climate change potential could be realized by adopting improved firewood stoves and improved charcoal stoves in combination with improved kiln technology, relative to traditional stove technologies for both fuel sources. GCCP of biomass pellet and improved firewood stoves is relatively similar, considering the overlap in uncertainty range. Stove emission inventories register similar CO_2 emissions for the two stove types despite a significant difference in stove thermal efficiency.

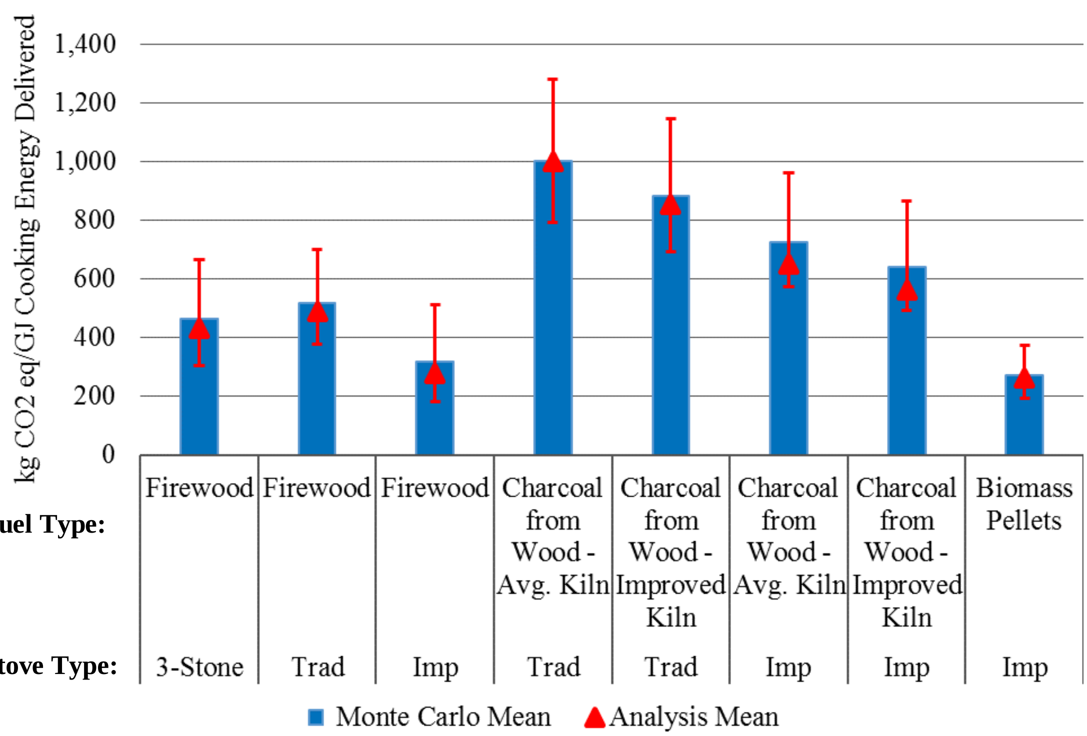


Figure 7-8. Kenya GCCP uncertainty analysis results for wood-based cooking fuels modeled with various allocation approaches and stove technologies.

(Axis Abbreviations: Imp = Improved, Trad = Traditional)

Upper boundaries of PMFP impact tend to be higher for solid firewood than for charcoal. In general, the uncertainty range for PMFP impact of firewood options is wider than for other fuel and stove types. There is a high degree of overlap between the uncertainty ranges of the firewood and charcoal cookstoves. From the perspective of PMFP impacts, it is challenging to justify the promotion of one traditional cooking fuel type over the other, although the higher end of the potential impact range associated with firewood stoves can be avoided by promoting improved firewood and charcoal stoves. Improved charcoal stoves and kiln technology realize a significant reduction in PMFP as compared to traditional stoves and average kiln performance. Biomass pellets present an opportunity to drastically reduce PMFP impacts while still utilizing firewood resources.

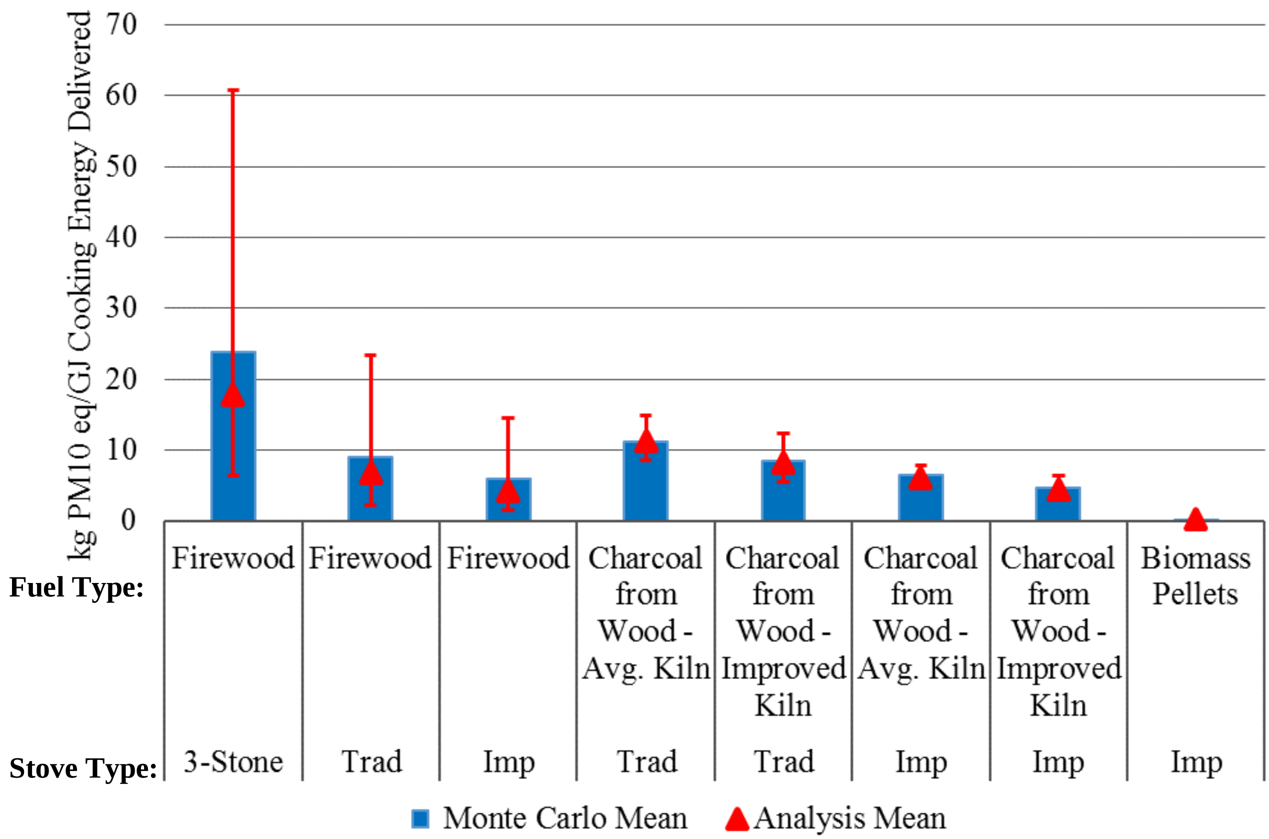


Figure 7-9. Kenya PMFP uncertainty analysis results for wood-based cooking fuels modeled with various allocation approaches and stove technologies.

(Axis abbreviations: Imp = improved, Traditional = trad, Avg = average)

In general, as evident in Figure 7-10, Kenyan cooking fuels currently relied upon do not produce significant quantities of emissions that contribute to TAP, as demonstrated by the normalized results. The fuels demonstrating the highest TAP impact in Figure 7-10 are associated with acidifying emissions in their supply-chains. TAP of Kenyan electricity production is largely due to the country’s reliance on fuel oil for approximately one-third of its current electricity grid mix. The TAP impact of sugarcane ethanol is associated with ammonia emissions during agricultural production of sugarcane. Variable rates of nitrogen fertilization and nitrogen volatilization as ammonia are responsible for the wide uncertainty range projected for sugarcane ethanol.

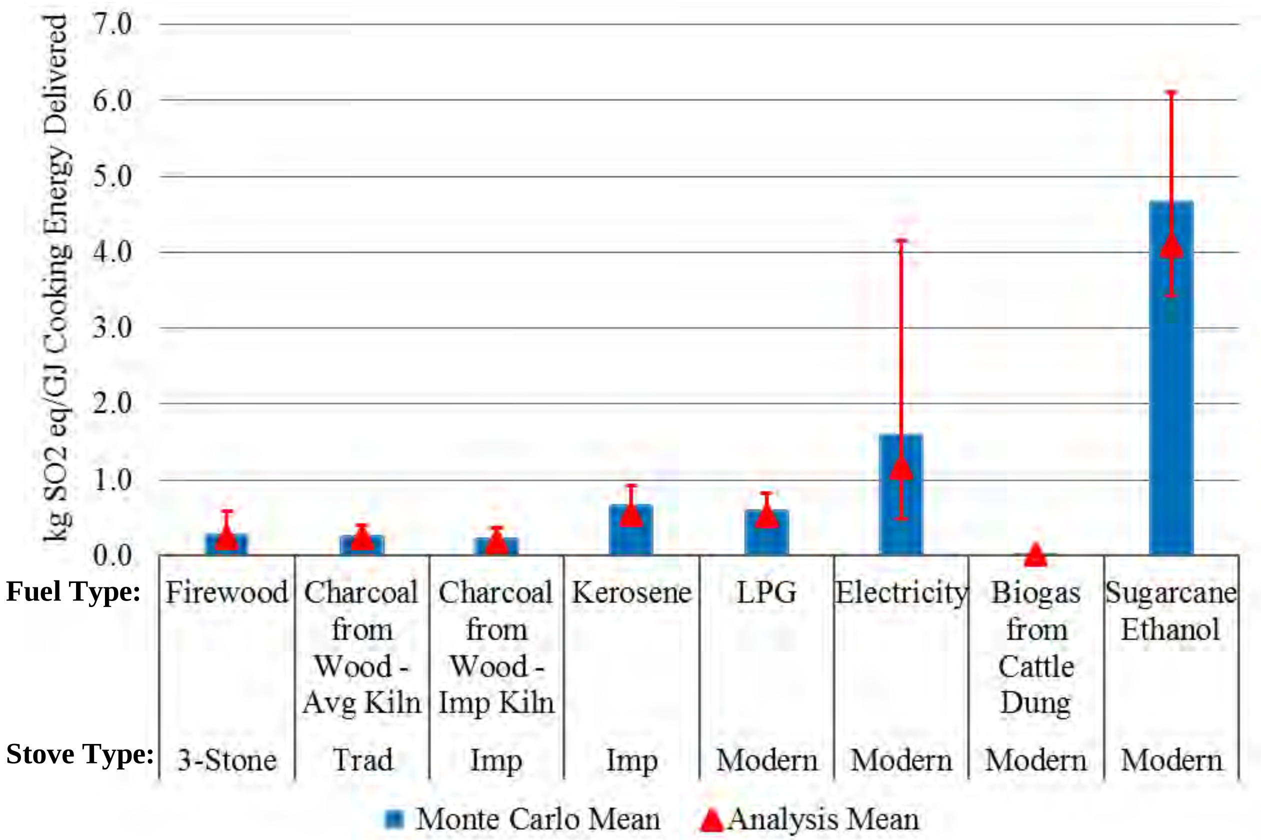


Figure 7-10. Kenya TAP uncertainty analysis results for select cooking fuels modeled with various allocation approaches and stove technologies.

(Axis abbreviations: Imp = improved, Trad = traditional, Avg = average)

8. LCA RESULTS FOR GHANA

Firewood and charcoal are the predominant cooking fuels used in Ghana today, providing approximately 42 and 32 percent, respectively, of national cooking energy (GLSS6 2014). The current cooking fuel mix in Ghana has seen a dramatic drop in the use of firewood since the late 1990s in favor of LPG use. Charcoal use has increased only slowly from 26 percent of the cooking fuel mix in the mid-1980s to a peak of 34-37 percent in the year 2008 (GLSS1 2008). Results presented here describe the potential shifts in environmental impact if this trend continues and help demonstrate if other sources of cooking energy provide a favorable alternative to LPG. Ghana relies more heavily on charcoal use than other nations studied and for this reason, the environmental effect of improved charcoal stove and kiln technology is of particular interest.

Table 8-1 presents summarized LCA results for all fuel types and impact categories considered for Ghana. The results are representative of baseline assumptions concerning cooking fuel mix, stove technology use, stove thermal efficiency, electricity grid, and forest renewability factor. Charcoal from wood has the greatest GCCP impact per GJ of delivered cooking energy. In general, GCCP impacts for wood-based fuels in Ghana are slightly greater than those reported for India and China and are approximately 50 percent lower than those reported for Kenya. Differences observed between nations are primarily due to current technology adoption and forest renewability factors specific to each country. Like Kenya, energy demand and FDP of kerosene and LPG is significantly greater than it is for India and China due to inefficient refinery operations. Other single fuel impact scores show reasonable order of magnitude alignment with results for other countries.

Table 8-1. Summary Table of Single Fuel Results by Impact Category (Impact/GJ Delivered Cooking Energy) – Ghana

Fuel Type	GCCP	CED	FDP	WDP	PMFP
	(kg CO_2 eq)	(MJ)	(kg oil eq)	(m^3)	(kg PM_{10} eq)
Firewood	228	9.20E+3	7.36E-3	8.16E-5	15.5
Crop Residue	120	1.04E+4	7.56E-3	8.32E-5	15.4
Charcoal from Wood	712	1.57E+4	10.6	0.135	10.2
Biomass Pellets	152	4.35E+3	21.2	0.868	0.162
Kerosene	284	8.24E+3	193	0.078	0.104
LPG	274	7.67E+3	179	0.127	0.114
Electricity	259	7.94E+3	150	7.58	0.310
Sugarcane Ethanol	94.3	1.32E+4	27.2	644	4.26
Biogas from Cattle Dung	13.4	4.21E+3	-	3.29	0.187

Table 8-1. Summary Table of Single Fuel Results by Impact Category (Impact/GJ Delivered Cooking Energy) – Ghana

Fuel Type	POFP (kg NMVOC)	FEP (kg P eq)	TAP (kg SO_2 eq)	ODP (kg CFC-11 eq)	BC (kg BC eq)
Firewood	5.99	9.12E-3	0.230	6.77E-11	3.33
Crop Residue	9.02	9.37E-3	0.616	6.96E-11	3.36
Charcoal from Wood	30.1	0.016	0.335	9.41E-8	2.49
Biomass Pellets	1.51	6.14E-3	0.206	6.83E-8	0.026
Kerosene	1.48	1.49E-3	0.239	3.09E-8	0.012
LPG	1.39	3.30E-3	0.265	6.42E-8	0.011
Electricity	1.39	1.97E-3	1.10	3.61E-7	-0.030
Sugarcane Ethanol	0.457	0.034	4.10	2.77E-6	0.755
Biogas from Cattle Dung	0.084	-	5.13E-3	-	0.040

8.1 Cooking Fuel Mix Scenario Results – Ghana

Cooking fuel mix scenario results provide the most comprehensive perspective on the options for cookstove sector improvements included in the second phase of this project. Table 8-2 provides a guide to interpretation of bar axis labels.

Table 8-2. Cooking Fuel Mix Scenario Technology Options (*Figure Key*)

Fuel Mix Scenario Parameter Options	Description
Current Tech-Current Eff-Current Grid[1]	Assumes current stove technology, current average stove thermal efficiency values, and 2013 electrical grid mix.
Imp Tech-Current Eff-Current Grid	Assumes improved stove technology use, current average stove thermal efficiency values, and 2013 electrical grid mix.
Imp Tech-Imp Eff-Current Grid	Assumes improved stove technology use, improved stove thermal efficiency values, and 2013 electrical grid mix.
Imp Tech-Imp Eff-Clean Grid	Assumes improved stove technology use, improved stove thermal efficiency values, and the use of clean electricity in electric cookstoves.

[1] Tech = stove technology, Imp = improved, Eff = stove thermal efficiency

Figure 8-1 presents GCCP results for each cooking fuel mix scenario and the range of technology options included. GCCP impact is more sensitive to improvements in stove technology than to the future cooking fuel mix changes presented here. The BAU 2030, Moderated Growth, and Fast Growth scenarios do not deviate more than six percent from current GCCP impact in the absence of stove technology and efficiency upgrades. Stove technology upgrades for these three scenarios reduce GCCP impact scores by between 28 and 33 percent relative to the baseline scenario. Stove efficiency upgrades for each stove type have the potential to reduce impact by a further six percent for each of the three scenarios.

The Diverse Fuel Mix scenario realizes a 14 percent reduction in GCCP relative to the baseline, based on changing the cooking fuel mix alone. Adoption of improved stove technology for this scenario increases that reduction to 35 percent with stove thermal efficiency improvements adding an additional nine percent reduction relative to baseline impacts. The proposed cooking fuel mix substitutions demonstrate limited effect on GCCP impact as a result of similar GCCP impact scores for LPG and firewood, which largely replace one another in the various fuel mix scenarios. Stove technology and efficiency upgrades achieve most of their reductions for firewood and charcoal fuel types. Scenario results are not greatly affected by the introduction of a cleaner electrical grid as reliance on electricity in the scenario cooking fuel mixes is limited.

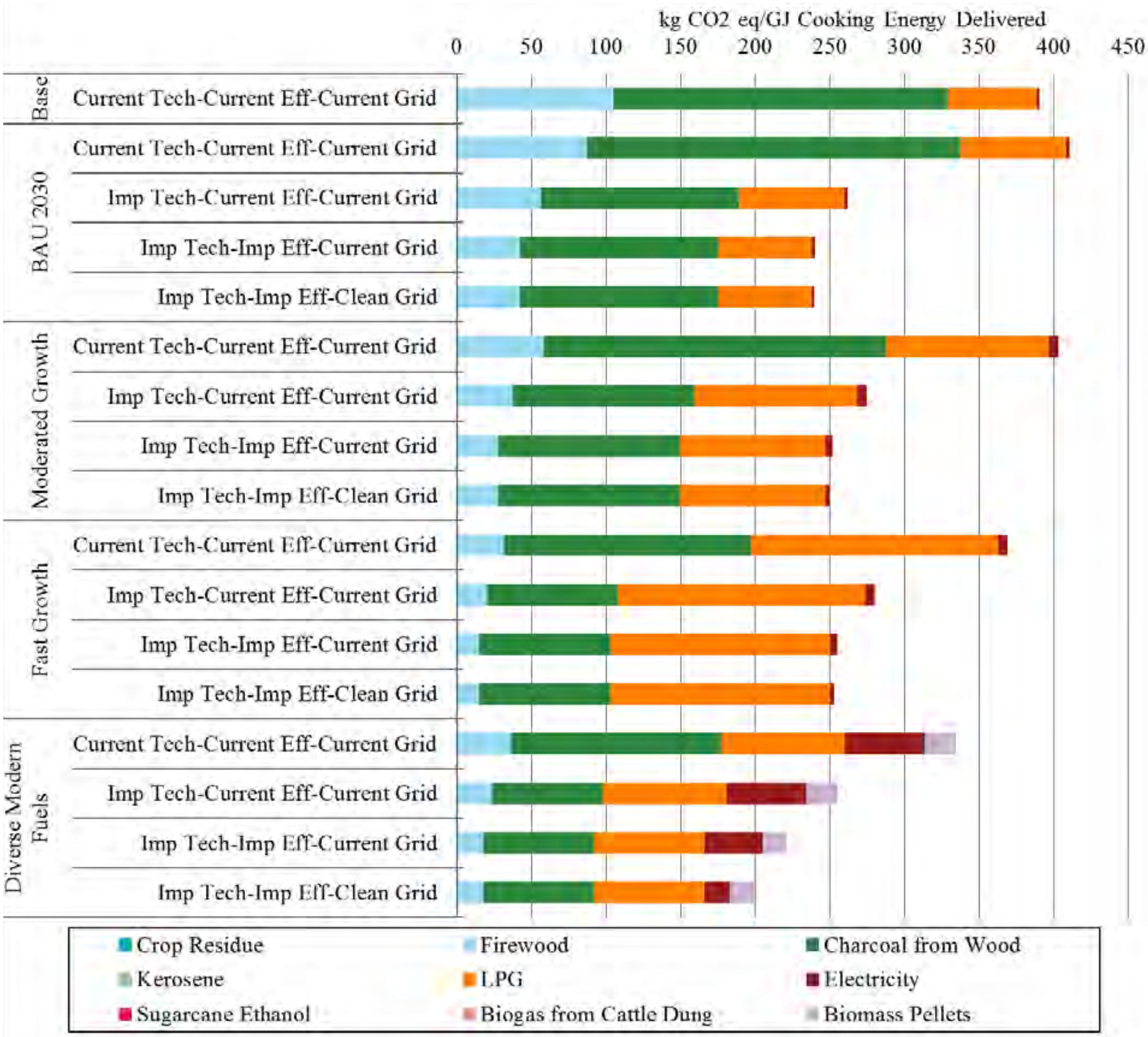


Figure 8-1. Ghana GCCP cooking fuel mix results.

(Axis abbreviations: Imp = improved, Tech = stove technology, Eff = stove efficiency)

Figure 8-2 shows cooking fuel mix scenario results for PMFP. PM emissions respond strongly to fuel mix shifts due to the low PMFP of LPG, which increases as a component of the cooking fuel mix in all future projections. LPG use increases to comprise 60 percent of the cooking fuel mix in the Fast Growth scenario, and PMFP impact is reduced to just 45 percent of its current level. Layering on stove technology and efficiency upgrades yields a 73 percent reduction in impact relative to the baseline. The Diverse Modern Fuel mix realizes PMFP reductions within a few percentage points of those described for the Fast Growth scenario.

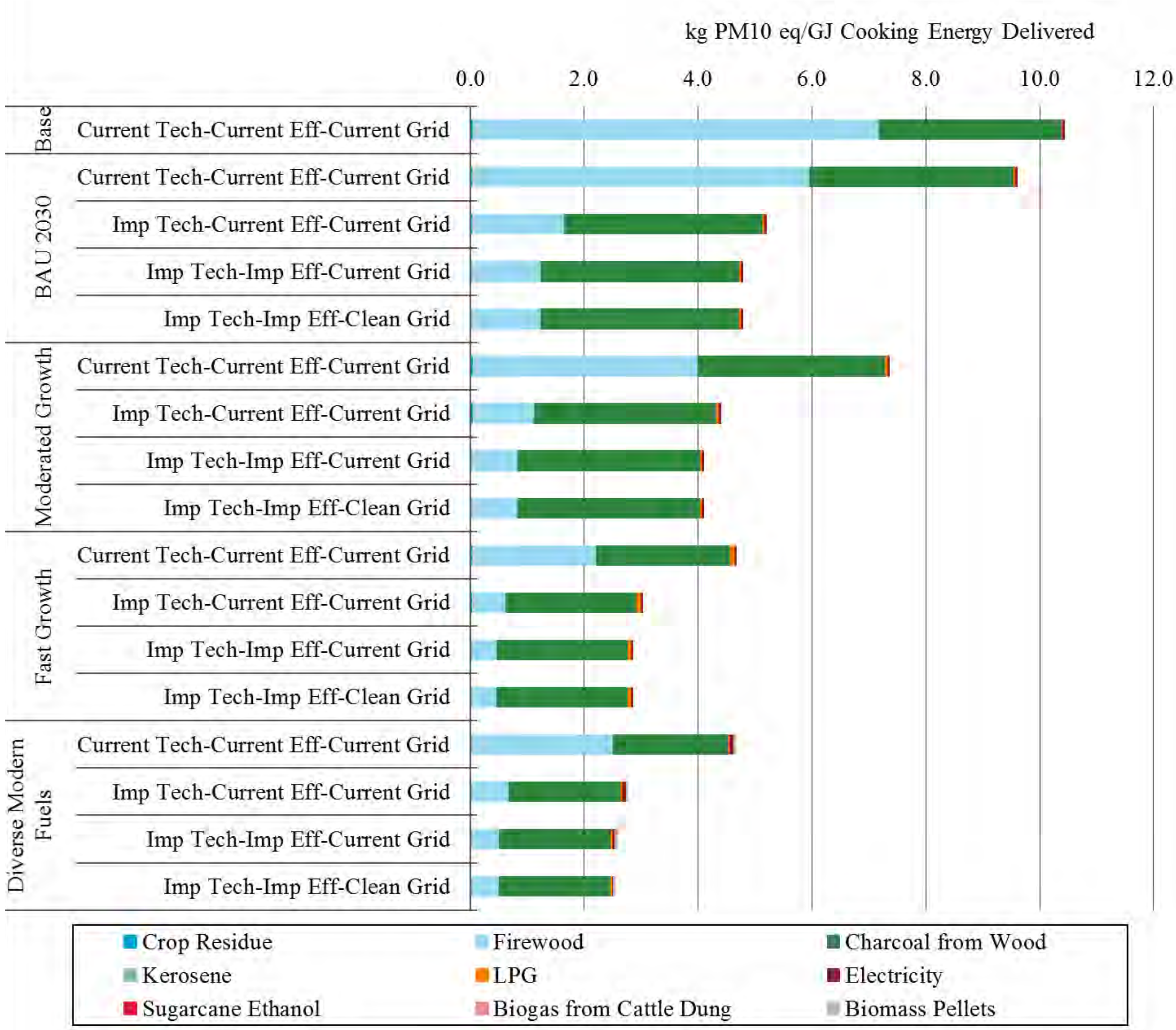


Figure 8-2. Ghana PMFP cooking fuel mix results.

(Axis abbreviations: Imp = improved, Tech = stove technology, Eff = stove efficiency)

Figure 8-3 depicts the CED for cooking fuel mix scenarios in Ghana. Shifts in fuel mix alone result in a maximum reduction in CED of 16 percent, which is associated with the Diverse Modern Fuel mix. CED reductions are more sensitive to the proposed technology and efficiency upgrades than they are to fuel mix shifts. Between 67 and 100 percent of potential CED reductions are attributable to stove technology and efficiency upgrades. Depending upon the scenario, CED reductions between 38 and 50 percent are possible. Most of the improvements in energy demand are attributable to a reduced reliance on solid wood fuel and charcoal.

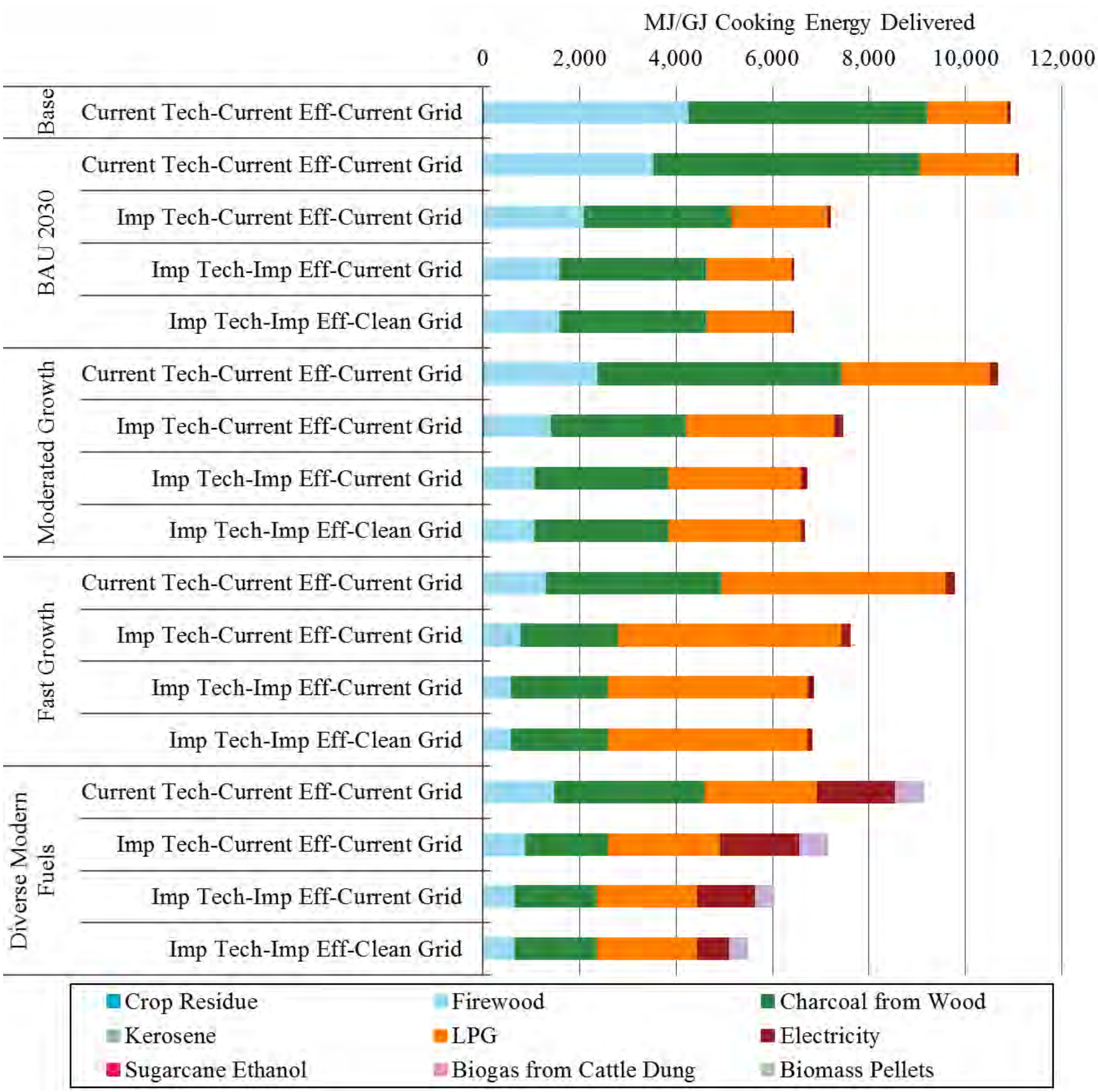


Figure 8-3. Ghana CED cooking fuel mix results.

(Axis abbreviations: Imp = improved, Tech = stove technology, Eff = stove efficiency)

8.2 Baseline Normalized Results – Ghana

The concept and methodology behind a normalized presentation of results was introduced in detail in Section 4.6. Generally, the results show which impact categories are most strongly linked to the activity of study. If normalization factors were perfectly calibrated, the sum of personal equivalent emissions for all sectors would equal the population of a given country, which for Ghana is approximately 26 million people. However, normalized emission estimates are uncertain due to lack of geographic granularity and the ever-changing nature of national or global level estimates for many categories, indicating that the relative magnitude of results and not the specific person equivalency value is of greater importance and validity. Normalized results indicate only the level of the cookstove sector contribution to national economy-wide impacts, they do not imply that impact categories are of greater or lesser significance.

Normalized results for Ghana, displayed in Figure 8-4, indicate that at the national level, CED, PMFP, POFP, and BC impacts are those most prominently linked to the cooking sector. Results generally align with the findings for other countries. However, normalized CED is greater for Ghana than it is for other nations, which is due primarily to two factors. First, Ghana has the lowest per capita energy demand of any of the nations studied, meaning there are fewer total economy energy impacts from other sectors. Second, Ghana relies on charcoal for nearly one-third of national cooking energy, which leads to a greater CED per GJ of delivered cooking energy than is observed in other nations. Normalized results for POFP are also somewhat greater for Ghana than for other nations, primarily attributable to charcoal use and production. PMFP and BC results are primarily associated with the use of charcoal and firewood, and drop dramatically as LPG use increases as a component of the fuel mix. FDP, WDP and TAP show the potential for modest increases in normalized impacts if Ghana moves towards implementation of a fuel and technology mix in line with the options analyzed in this study.

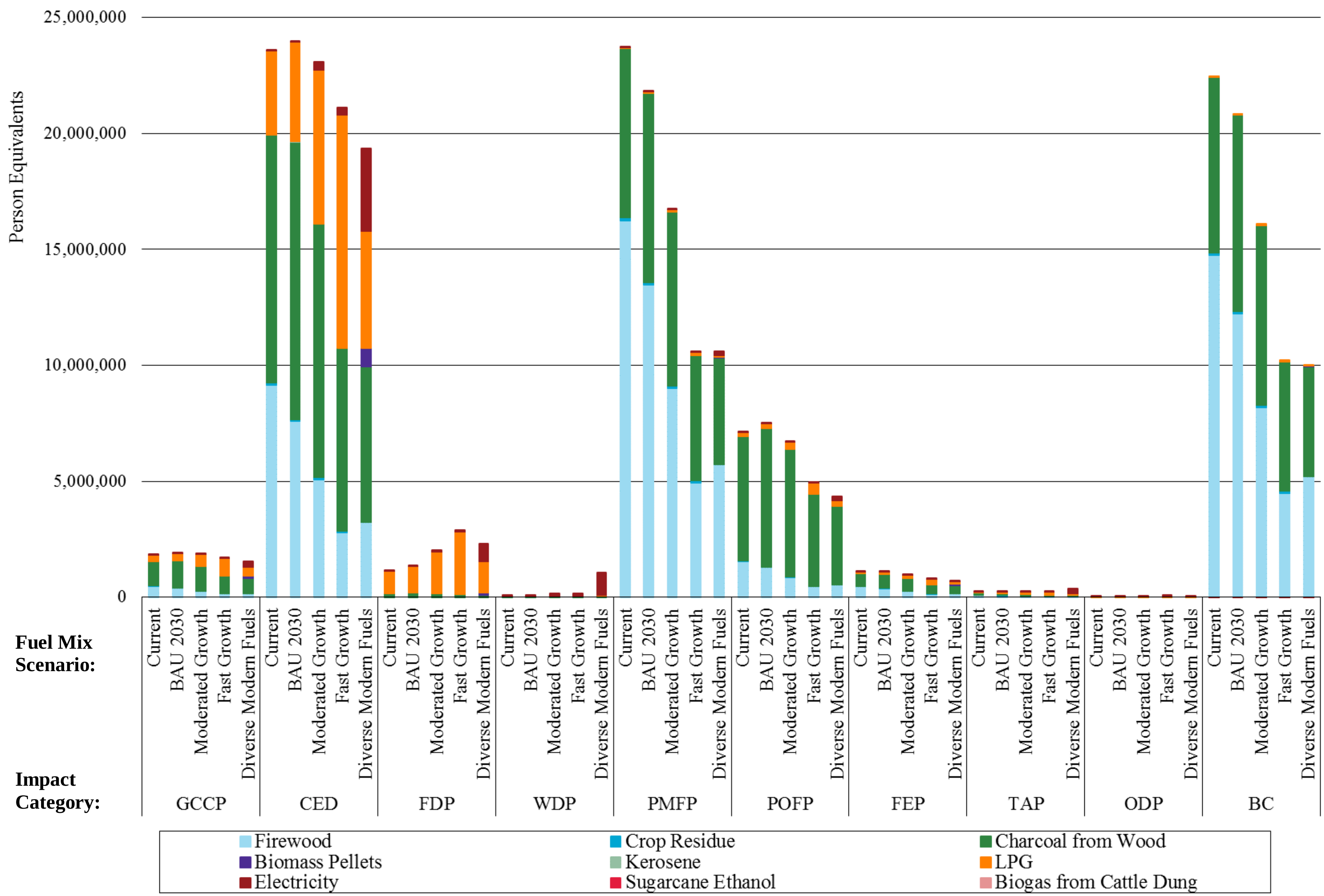


Figure 8-4. Ghana normalized LCA results.

8.3 Stove Efficiency Sensitivity – Ghana

Figure 8-5 shows the GCCP of select stove groups, highlighting the potential effect of improved thermal efficiency on reductions in environmental impact. Each of the bars is labeled with the associated current or future improved stove thermal efficiency value for that stove group. The figure shows that traditional fuels with lower starting thermal efficiencies have significantly more relative potential to reduce GCCP emissions through adoption of both improved stove technology or use of the best performing traditional stoves. Modern fuels have already realized high stove thermal efficiencies and therefore, realizing substantial relative gains is challenging. For example, the best performing traditional firewood stove produces approximately 38 percent less GHG emissions than does the current average stove. The percent reduction achieved by upgrading LPG stoves is only 11 percent. Even larger gains are possible for charcoal users as a result of potential efficiency upgrades at both the stove and the kiln. The figure shows that, considered in isolation, stove efficiency and kiln improvements have similar potential to improve the performance of a traditional charcoal stove, both with percent reductions in GCCP impact between 33 and 38 percent. Combining these strategies yields a total GHG emission reduction of approximately 58 percent. As the figure shows, thermal efficiency is not the only, or even the predominant, determinant of GCCP, but it does have a significant effect on stove performance for a given stove grouping or fuel type.

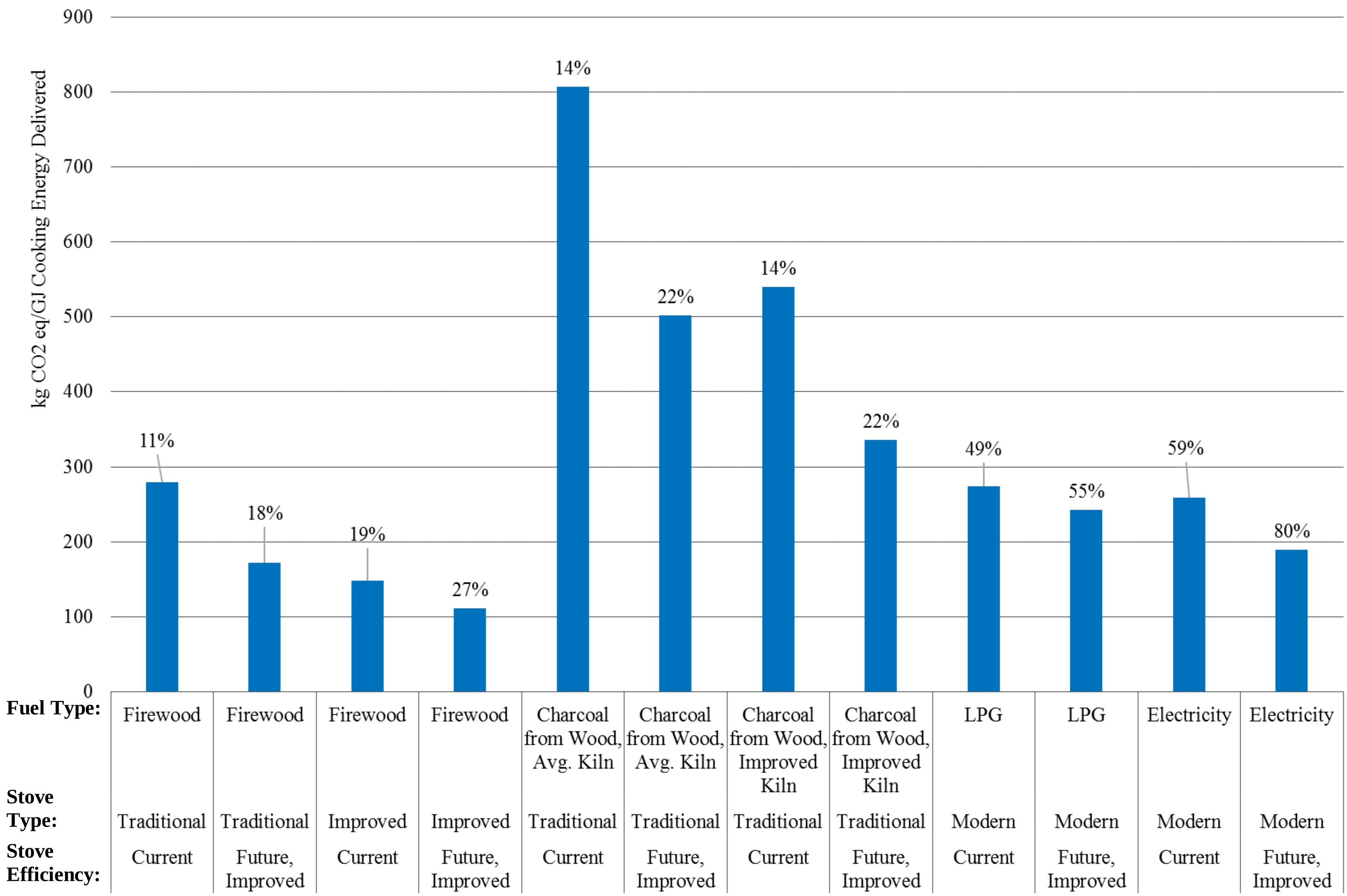


Figure 8-5. GCCP effects of stove thermal efficiency in Ghana for various kiln and stove technologies.

8.4 Electricity Grid Mix Sensitivity – Ghana

The current electrical grid in Ghana is fueled by hydropower, oil, and natural gas in descending order of contribution (IEA 2013d). All potential future electrical grids, as described by Ghana's Energy Commission, indicate future reliance on a more diverse palette of fuel options. The primary trend projected by Ghana's Energy Commission is decreased reliance on hydropower as electricity demand grows. The three Ghana EC scenarios represent the full range of what the Ghana Energy Commission envisions as probable in the near term (GEC 2006), while the fourth Low Carbon scenario indicates the potential carbon footprint of a clean grid, which relies on Ghana's considerable solar, wind, and hydropower resources (IRENA 2013). The renewable and nuclear Ghana EC grid mixes achieve only moderate reductions in GCCP as compared to the present grid (Figure 8-6). The Ghana EC thermal scenario shows that if coal power is relied upon to service increasing demand, it is possible that the GCCP of electrical cookstove use will increase in the future. The Low Carbon electricity scenario produces approximately 115 kg of CO_2 equivalent emissions per GJ of delivered cooking energy, which is a 55 percent improvement as compared to electric cookstoves relying on the current grid.

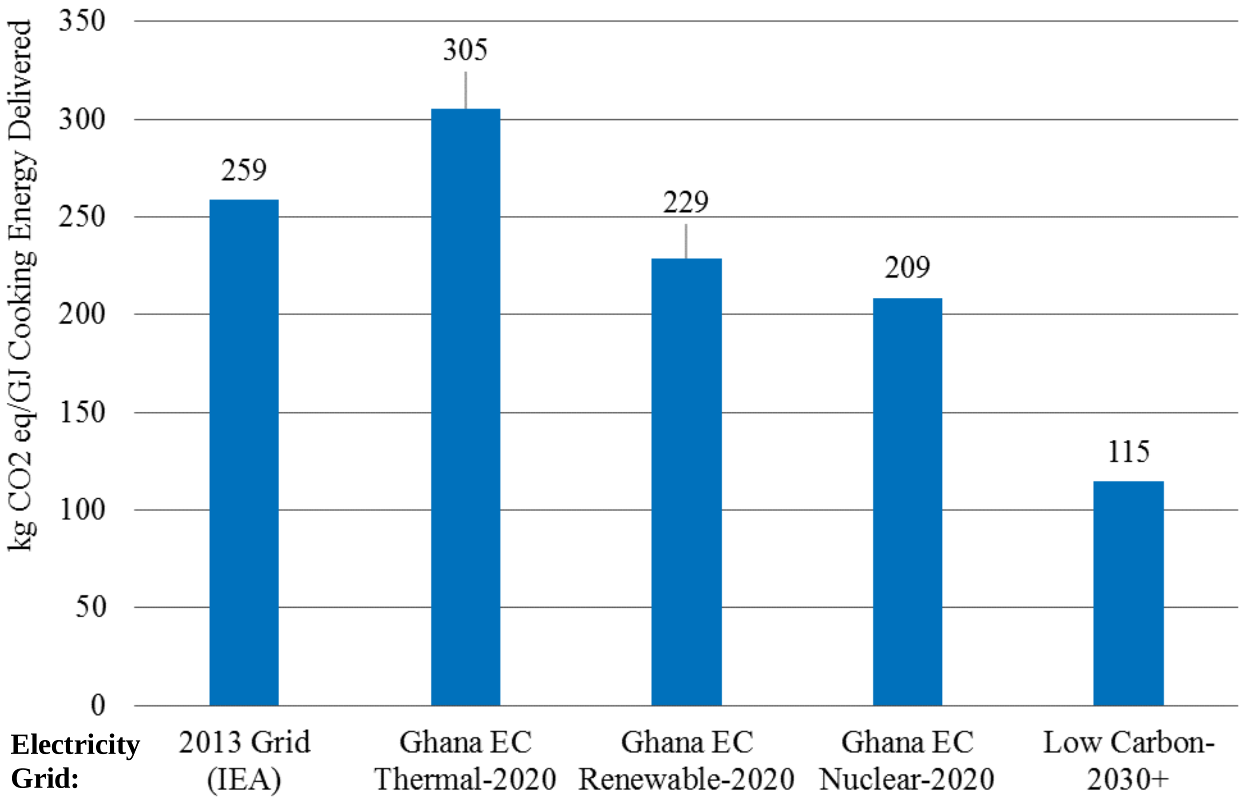


Figure 8-6. Ghana GCCP of electric cookstove use with various electrical grid mix options.

8.5 Forestry Renewability Factor Sensitivity – Ghana

Figure 8-7 shows the effect of forest renewability factors on the GCCP impact of wood-based fuels produced and consumed in Ghana. The high renewability factor (high renew.), which is presented as the baseline value for this study, is derived from the WISDOM database (Drigo 2014) and indicates that approximately 71 percent of forest products in Ghana are produced renewably. A method previously used to determine forest renewability factors indicated that 100 percent of forest land is managed unsustainably and therefore emissions associated with wood combustion are not considered to be carbon neutral (low renew.). The assumptions behind these two methods were discussed previously in Section 4.2.

The choice between forest renewability factors yields a 66 to 102 percent difference in impact score depending upon cooking fuel and stove type. The disparity between high and low renewability factors is greater in Ghana than it is for other countries studied. While the magnitude of GCCP impact varies for charcoal by a factor of two depending upon the renewability factor selected, the choice does not influence its performance relative to other fuels. Charcoal exhibits the highest GCCP impact regardless of renewability factor. The choice of renewability factor is, however, critical in determining the relative performance of firewood and biomass pellet cookstoves. The baseline high renewability factor yields GCCP impact scores that are lower than the modern liquid and gas fossil fuel options. Assuming the low renewability factor, even the most efficient option, biomass pellets, is unable to produce GCCP impacts that are competitive with the modern fossil fuels.

Forest renewability factors are based on current estimates regarding the sustainability of forestry operations. If significant efforts are made to improve the efficiency of firewood use, for example through the widespread adoption of pelletized wood stoves, then the renewability factor could improve over time. General improvements in forestry practices such as increased effort to replant following harvest, could also improve the sustainability of national forestry operations. Alternatively, increased consumer demand for wood products without the adoption of improved practices will surely cause the sustainability of forestry operations to deteriorate.

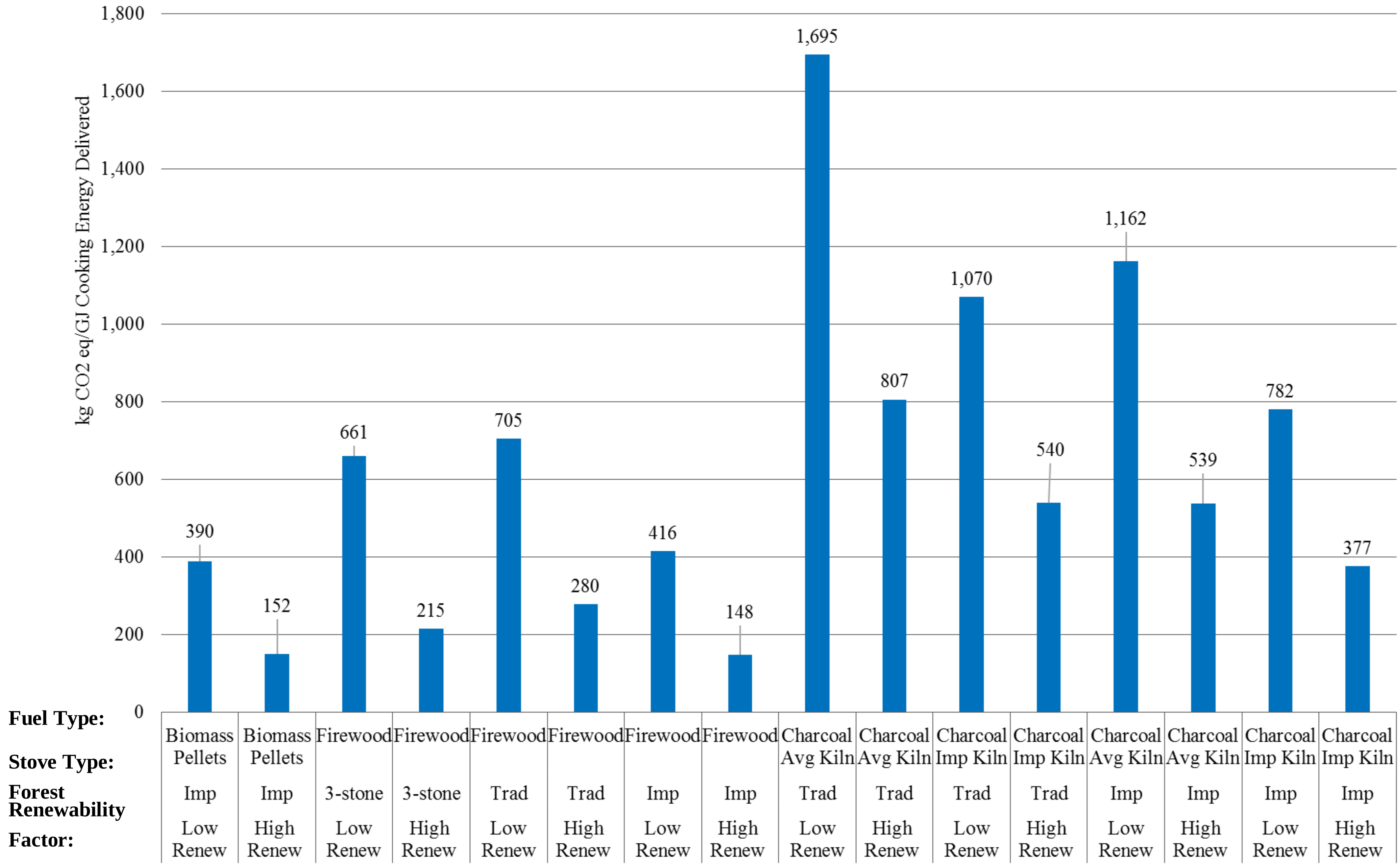


Figure 8-7. Comparative effect of forest product renewability assumption on GCCP in Ghana.

(Axis abbreviations: Imp=improved, Trad=traditional, Renew=renewable)

8.6 Stove Group Uncertainty Results – Ghana

Figure 8-8 shows CED stove group uncertainty results for a wide range of fuel and stove technology options in Ghana. All results in the figures incorporate baseline LCA modeling conventions. The height of the bar in each figure represents the Monte Carlo mean around which the error bars are centered. The analysis mean (triangle in figure) for each impact category is the characterized expected value as it was entered into openLCA. The analysis and Monte Carlo mean deviate from one another depending upon the distribution used, and in the case of lognormally distributed data, depending upon the geometric standard deviation.

Uncertainty ranges for CED tend to be more narrow, as a percentage of mean impact, than they are for other impact categories. The reduced energy demand potential of biomass pellets as compared to three-stone fires is apparent in the figure and indicates one possible avenue for reducing wood consumption in Ghana. The figure also shows the high-energy demand of charcoal use when traditional stoves are used to burn charcoal from average kilns. Significant reductions in CED are possible if improved charcoal stoves and improved kiln technology are adopted. Despite CED reductions associated with improved charcoal technology, this fuel type and the charcoal supply chain are unable to compete with the best available improved firewood cookstoves or biomass pellet cookstoves. Sugarcane ethanol demonstrates the second highest CED of all cooking options in Ghana. The energy demand of LPG and electric cookstoves in Ghana is higher than the energy demand associated with the same cooking options in India or China. Elevated CED for both fuel options is due to petroleum refining, which also effects electric stove use due to Ghana’s heavy reliance on fuel oil as a source of electrical energy.

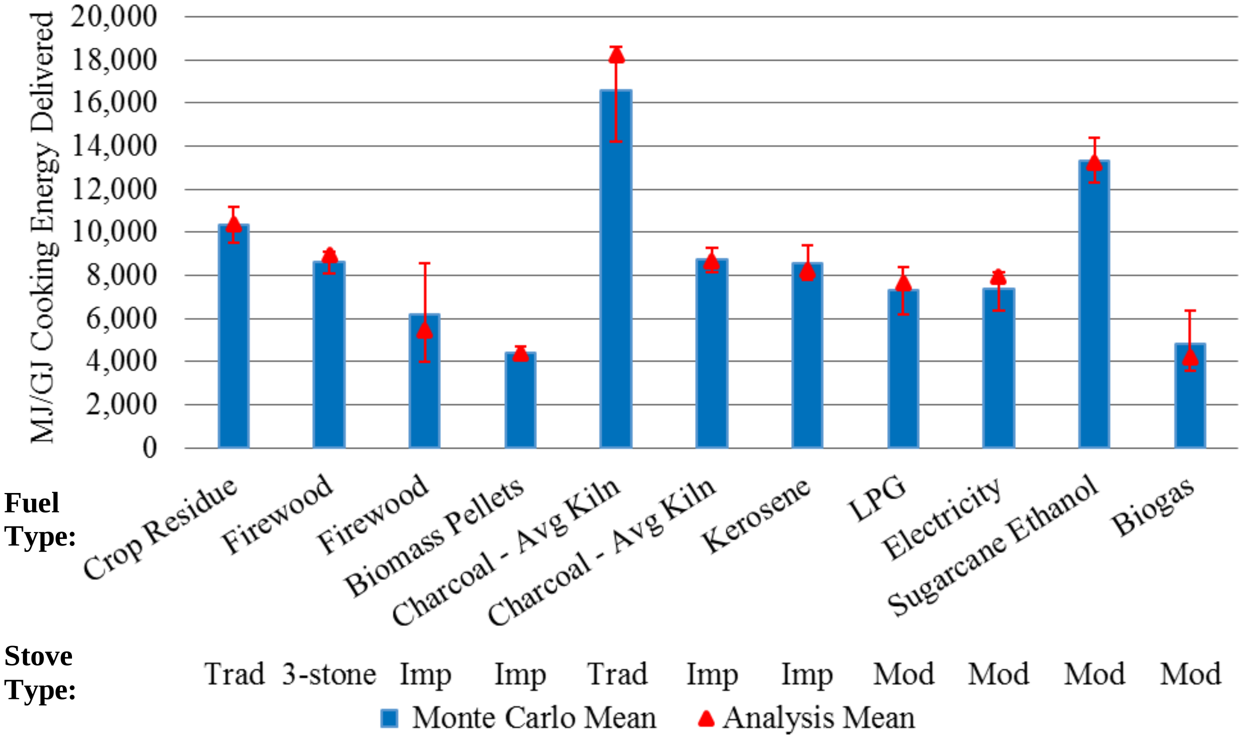


Figure 8-8. Ghana CED uncertainty analysis results for select cooking fuels modeled with various stove technologies.

(Axis abbreviations: Imp=improved, Trad=traditional, Mod=modern)

Figure 8-9 shows POFP stove group uncertainty results for a wide range of fuel and stove technology options in Ghana. Charcoal cookstoves, particularly those relying on average kiln technology, demonstrate high POFP impacts that are associated with a high degree of uncertainty. As with other impact categories, significant potential for impact reduction is possible if either improved stove and kiln technologies or modern fuels are adopted. The use of biomass pellets can produce low POFP impacts similar to those associated with modern fuels.

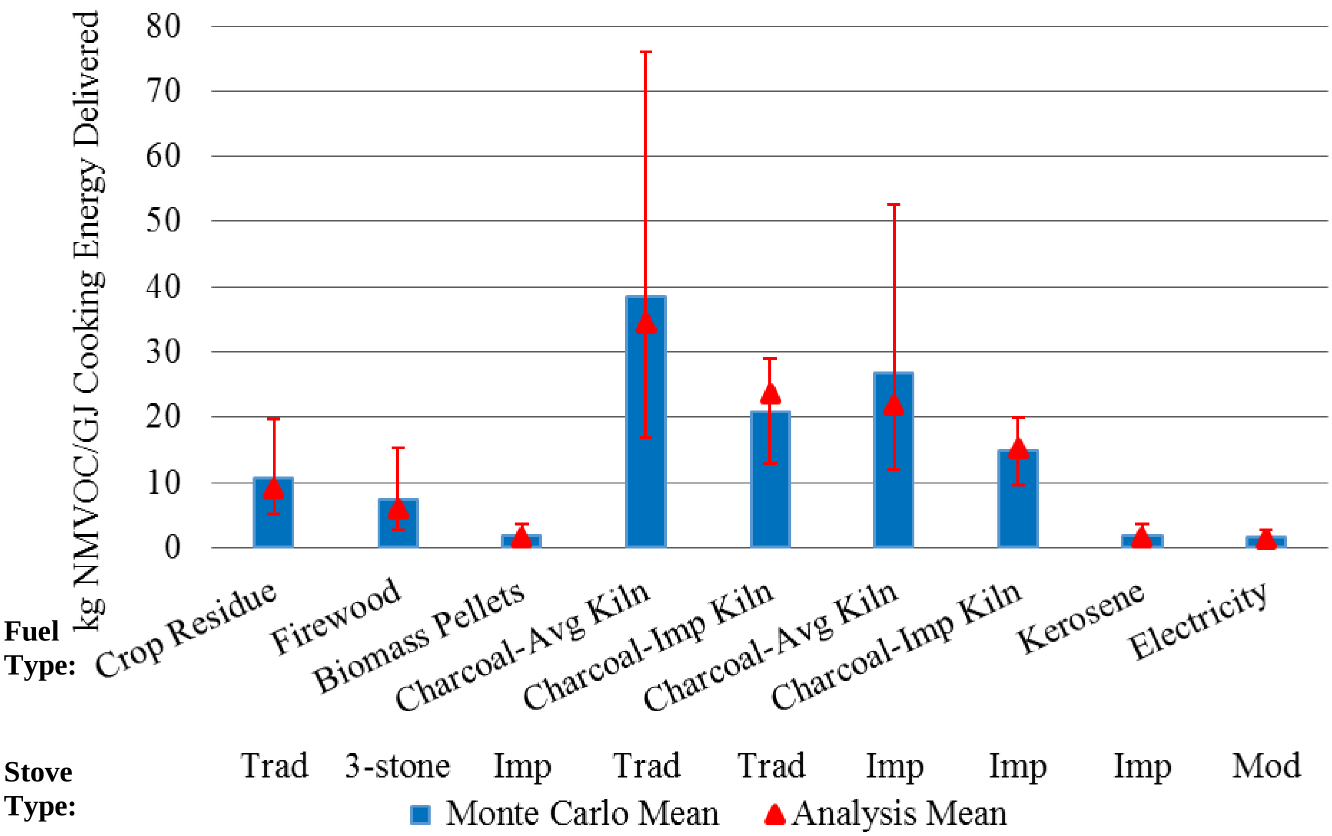


Figure 8-9. Ghana POFP uncertainty analysis results for select cooking fuels modeled with various stove technologies.

(Axis abbreviations: Imp=improved, Trad=traditional, Mod=modern)

9. KEY TAKEAWAYS BY COUNTRY AND STUDY CONCLUSIONS

This section highlights several key takeaways for each country studied, followed by noteworthy conclusions and trends for this phase of work.

9.1 Key Takeaways

This section describes the key takeaways common to each country, followed by findings unique to the countries studied.

9.1.1 Findings Common to all Countries

- Normalized results for all countries show that BC and PMFP impact categories are strongly linked to the cooking sector. Results also show that impacts in these two categories are sensitive to the projected future fuel mix and stove technology shifts considered in this study, indicating multiple pathways by which to reduce impacts attributable to the cooking sector.

- Utilization of modern cooking fuels such as liquefied petroleum gas (LPG), natural gas, biomass pellets, and ethanol resulted in significant reductions in PMFP and BC, categories strongly linked to the cooking sector.

- Normalized results confirm that traditional fuels pose a significant risk to human health (e.g., due to PMFP). The possibility of using renewably sourced wood fuel in combination with the adoption of improved or pelletized stoves could significantly reduce hazardous emissions while still allowing the use of traditional biomass resources.

- The sensitivity analysis shows that a significant range in potential environmental impact exists between the worst and best performing cookstoves within a given stove type (e.g. firewood traditional).

- Biogas and biomass pellets hold significant potential to reduce household air emissions attributable to the cooking sector.

- Updated LCI information for the agricultural production of sugarcane indicates significant upstream environmental impacts associated with ethanol production.

9.1.2 India

- Normalized BC impacts in India are high relative to other nations and are disproportionately influenced by the use of dung and crop residues in the current cooking fuel mix.

- The current, coal heavy electricity mix in India and high electrical grid losses contribute to the poor performance of electric cookstoves relative to other modern fuel options.

- Realizing further GCCP impact reductions will be a challenge for India as the country moves to adopt modern fossil-based cooking fuels. GCCP of the current Indian cooking fuel and stove technology mix is at minimum 49 percent lower than that realized by the other nations studied due to India's continued reliance on biomass fuels, relatively high baseline forest renewability, and an absence of significant contributions from stoves that exhibit particularly poor performance such as traditional coal powder and charcoal cookstoves, all of which drive up GCCP impact in the other countries.

9.1.3 China

- In China, one-third of cooking fuel energy is produced from coal, which disproportionately contributes to the country's normalized PMFP and BC impacts. Potential reductions in environmental impact realized by switching from coal powder to advanced forms of coal consumption such as honeycomb briquettes or coal gas provide a robust option for consistently improving performance of the cooking sector across all impact categories.

- The current coal-heavy electricity mix in China results in poor performance of electric cookstoves for most impact categories assessed relative to other modern fuel options. Upgrades to China's electricity sector will be required for electric cookstoves to achieve environmental impact scores in line with, or better than, other modern fuels.

9.1.4 Kenya

- Scenario results show that reductions in Kenyan cooking sector emissions, compared to other countries studied, are more sensitive to adoption of improved stove technologies and thermal efficiencies, when holding cooking fuel mix constant. This is because Kenya currently relies heavily on three-stone fires and traditional wood stoves, which are associated with low thermal efficiencies and notable air emissions during cookstove use.

- Forest renewability is important in determining if the best performing wood-based options, biomass pellets and improved firewood stoves, can compete with the GCCP of modern liquid and gas fuel options. This is especially true for Kenya, which has the lowest forest renewability among the four study nations.

- Low availability of renewable wood resources in Kenya indicates that following Ghana's lead in pursuing increased charcoal use as a means of improving urban air quality could lead to significant pressure on other environmental impact categories and forest resources. While charcoal may serve to reduce emissions in the household, it does not reduce cumulative emissions across the supply-chain and serves as an inefficient use of forest resources.

- The electricity grid in Kenya has the lowest GCCP of all nations studied due to the prevalence of hydropower and geothermal energy in their electrical grid mix.

However, Kenya currently has the lowest national electrification rate, 23 percent, of any of the four countries studied (World Bank 2012). Electricity demand and generation capacity are expected to rise dramatically in the next 20 years, and the projected grid mixes yield further improvements in environmental performance. Electricity may prove a viable alternative to LPG and kerosene in urban Kenya if electrification and generation grow as expected.

9.1.5 Ghana

- Ghana demonstrates the second highest sensitivity to improvements in stove technology and efficiency, following Kenya, indicating the potential to reduce cooking sector emissions even in the absence of cooking fuel mix shifts.

- Of the four study nations, Ghana is most heavily reliant on charcoal energy as a source of cooking fuel (GLSS6 2014). Significant improvements in environmental performance are possible through improved charcoal stove and kiln technology adoption. However, even assuming the most optimistic adoption of charcoal technology, this fuel demonstrates consistently poor environmental performance relative to other cooking options and places a heavy burden on forest resources.

- Normalized CED of Ghana's cooking sector is significantly higher than that realized for other nations, which is due largely to inefficient energy conversion in charcoal kilns and the LPG refining process, as well as lower overall national per capita energy consumption for all sectors compared to national per capita energy use in the other study countries.

9.2 Conclusions

Normalized results across the nations studied agree that, at the national level, the cooking sector has the greatest potential to contribute to BC and PMFP economy-wide impacts. Cooking fuel mix results show that BC and PMFP can both be reduced dramatically by strategies that focus either on changing the cooking fuel mix or through the adoption of improved stove technologies. The latter strategy is particularly effective for nations and fuels that currently rely most heavily on traditional technologies. Firewood use in Kenya, for example, is still largely reliant on the use of three-stone fires, and consequently huge gains in fuel efficiency and associated emissions reductions are possible via technology improvements alone.

Normalized CED also tends to reveal a significant link between household cooking and national energy demand, but the results between countries vary. China and Ghana represent the extreme ends of the spectrum with China demonstrating the lowest normalized CED scores, in part attributable to real differences in current average CED of the national cooking fuel mix for each country, as China and Ghana have the lowest and highest CED per GJ of delivered energy, respectively. National per capita energy demand also plays a significant role in normalized impacts, and to the extent that this is responsible for differences in normalized impact, this difference reflects less on the cooking sector than it does on national energy use and the level of industrialization. The current average cooking fuel mix in India and China, for example, has similar CED values per GJ of delivered cooking energy, and yet normalized impacts are greater for India as a result of lower national energy use.

Reductions in some impact categories such as CED and GCCP are more challenging to achieve than either PMFP or BC emissions. The dramatic differences in PMFP impact that exists between traditional and modern fuels are significantly muted for GCCP and CED, thereby reducing the effectiveness of all but the most dramatic substitutions of fuel type and stove technology. CED and GCCP impact reductions are more easily achieved in China, Kenya, and Ghana due to the fact that all three nations currently rely heavily on either coal powder or charcoal, which are the poorest performing fuels for these impact categories considered in the respective nations, allowing for beneficial emission reductions regardless of what fuel substitution is made. Biogas demonstrates notably lower GCCP impact than any other fuel considered in the study. While GCCP is a critical impact category at the global level, it must be remembered that normalized results show that GCCP is not necessarily driven by the cooking sector in each study nation.

As discussed, two separate methodologies were considered over the course of this study to determine the fraction of forestry products that are renewably produced and are therefore carbon neutral. Significant differences in GCCP impacts result from the choice of methodology, and should be considered when evaluating results. For example, in China the choice of renewability factor is enough to influence whether adoption of modern fuels yields an increase, decrease, or no significant effect on emissions contributing to climate change. In Ghana, the choice of renewability factor is critical in determining the relative performance of firewood and biomass pellet cookstoves. The baseline high renewability factor yields GCCP impact scores that are lower than the modern liquid and gas fossil fuel options, whereas assuming the low renewability factor, even the most efficient option, biomass pellets, is unable to produce GCCP impacts that are competitive with the modern fossil fuels.

Consistent with the Phase I results, it is more challenging to realize cooking fuel mix level improvements in environmental performance than initial appearances imply. Particularly when looking at single fuel results where it is obvious that dramatic, often order of magnitude, differences in impact exist between the worst and best performing fuels in a given impact category. First, the 100 percent substitution that the differences in single fuel impact scores imply are not possible at the level of national cooking fuel mix. Additionally, realized reductions in aggregate impact scores of a fuel mix tend to be muted by canceling factors that occur when simultaneous shifts occur involving multiple fuel types. The Ghana Transition (for Kenya) scenario applicable to Kenya provides an example of this phenomenon. The scenario realizes a significant reduction in firewood use, which is offset by increases in charcoal and LPG consumption. Despite dramatic shifts in the underlying cooking fuel mix, the average GCCP increases by a few percentage points assuming stove and kiln technology remain constant.

The results also show that fuel mix substitutions designed to address a single impact category can lead to the exacerbation of other environmental impacts. For example, increases in charcoal use in Kenya or Ghana, which are primarily targeted to realize urban air quality improvements and reductions in PM emissions, have and will continue to lead to increased demand for firewood, greater GCCP impact, and increased PMFP emissions at the location of the kiln.

Results from the second phase of work confirm the single fuel outcomes of Phase I and provide a deeper understanding of the interplay between cooking fuel mix substitution, stove technology improvement, and stove thermal efficiency increases in achieving environmental impact reductions. The results presented in this report are only a subset of the full results available in the supporting files, and have been selected to highlight key trends while serving as a guide for interpretation of the full results available. The uncertainty analysis included in the second phase of work serves to increase confidence in how robust the differences in environmental performance observed are between cooking fuels. Areas where overlap in uncertainty ranges obscures clear distinctions between fuels highlight areas for potential future refinement and study. Normalized impacts help to focus our attention on the impact categories most strongly influenced by the cooking sector.

Finally, this analysis does not capture many social and economic dimensions that strongly influence the discussion surrounding appropriate policy options and technology choices within the cooking sector. The Global Alliance for Clean Cookstoves is furthering additional research in those areas, the results of which can be used in conjunction with findings in this study. The results presented here and in accompanying documents will provide the greatest insight when considered alongside information and indicators aimed at social and economic understanding of the cooking sectors in India, China, Kenya, and Ghana. Considerations for future cookstove LCA research include repeating this analysis for other countries such as countries in South America to expand the geographic relevance of this work.

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Appendix A
Baseline Single Cooking Fuel Results by Life Cycle Stage

Table A-1. Single Fuel LCIA Results by Life Cycle Stage for India[1]

per GJ delivered heat energy		Life Cycle Stage				
Impact Category:	*Fuel:*	**Feedstock Production**	**Fuel Processing**	**Distribution**	**Cookstove Use**	**TOTAL**
GCCP100 - Climate Change (kg CO2 eq)	Hard Coal	16.2	-	2.17	945	**963**
	Dung Cake	-	-	-	263	**263**
	Crop Residue	-	-	-	119	**119**
	Firewood	-	-	-	196	**196**
	Charcoal from Wood	-	227	00.0	176	**402**
	Kerosene	6.04	14.3	15.5	145	**180**
	LPG	5.09	10.6	14.5	127	**157**
	Natural Gas	0.031	3.86	1.87	112	**117**
	Electricity	-	-	-	457	**457**
	Sugarcane Ethanol	85.9	13.7	20.5	0.953	**121**
	Biogas from Cattle Dung	-	8.99	-	2.42	**11.4**
	Biomass Pellets	-	50.8	-	90.2	**141**
CED - Energy Demand (MJ)	Hard Coal	281	-	42.3	6.89E+3	**7.21E+3**
	Dung Cake	-	-	-	1.30E+4	**1.30E+4**
	Crop Residue	-	-	-	1.01E+4	**1.01E+4**
	Firewood	-	-	-	6.52E+3	**6.52E+3**
	Charcoal from Wood	-	5.06E+3	000	5.82E+3	**1.09E+4**
	Kerosene	120	335	257	2.37E+3	**3.09E+3**
	LPG	104	239	313	1.96E+3	**2.61E+3**
	Natural Gas	13.3	74.0	21.9	1.93E+3	**2.04E+3**
	Electricity	-	-	-	5.70E+3	**5.70E+3**
	Sugarcane Ethanol	2.30E+3	8.62E+3	345	2.08E+3	**1.33E+4**
	Biogas from Cattle Dung	-	2.11E+3	-	1.95E+3	**4.06E+3**
	Biomass Pellets	-	800	-	3.11E+3	**3.91E+3**
FDP - Fossil Depletion (kg oil eq)	Hard Coal	6.71	-	0.619	164	**172**
	Dung Cake	-	-	-	0.152	**0.152**
	Crop Residue	-	-	-	7.90E-3	**7.90E-3**
	Firewood	-	-	-	5.94E-3	**5.94E-3**
	Charcoal from Wood	-	5.12E-3	0.00	6.09E-3	**0.01**
	Kerosene	2.83	7.57	5.19	55.3	**70.9**
	LPG	2.44	5.39	6.48	44.4	**58.7**
	Natural Gas	0.316	1.74	0.461	46.1	**48.7**
	Electricity	-	-	-	122	**122**
	Sugarcane Ethanol	17.2	6.74	7.02	-	**31.0**
	Biogas from Cattle Dung	-	-	-	-	**-**
	Biomass Pellets	-	13.72	-	2.10E-4	**13.72**
WDP - Water Depletion (m3)	Hard Coal	0.312	-	0.020	0.066	**0.397**
	Dung Cake	-	-	-	1.68E-3	**1.68E-3**
	Crop Residue	-	-	-	8.72E-5	**8.72E-5**
	Firewood	-	-	-	6.54E-5	**6.54E-5**
	Charcoal from Wood	-	5.64E-5	0.000	6.36E-5	**0.000**

Table A-1. Single Fuel LCIA Results by Life Cycle Stage for India[1]

per GJ delivered heat energy		*Life Cycle Stage*				**TOTAL**
Impact Category:	*Fuel:*	**Feedstock Production**	**Fuel Processing**	**Distribution**	**Cookstove Use**	
	Kerosene	0.058	0.108	0.073	-	**0.239**
	LPG	0.049	0.076	0.069	-	**0.193**
	Natural Gas	3.00E-4	0.037	2.40E-3	-	**0.039**
	Electricity	-	-	-	3.25	**3.25**
	Sugarcane Ethanol	642	0.987	0.082	-1.00E-5	**643**
	Biogas from Cattle Dung	-	1.02	-	-	**1.02**
	Biomass Pellets	-	0.357	-	-5.28E-18	**0.357**
PMFP - Particulate Matter Formation (kg PM10 eq)	Hard Coal	1.66	-	4.94E-3	18.1	**19.8**
	Dung Cake	-	-	-	24.3	**24.3**
	Crop Residue	-	-	-	11.4	**11.4**
	Firewood	-	-	-	5.54	**5.54**
	Charcoal from Wood	-	18.8	0.000	1.73	**20.5**
	Kerosene	0.011	0.086	0.034	0.039	**0.171**
	LPG	9.59E-3	0.068	0.032	0.026	**0.136**
	Natural Gas	5.88E-5	7.21E-3	1.12E-3	0.011	**0.019**
	Electricity	-	-	-	1.91	**1.91**
	Sugarcane Ethanol	4.25	0.080	0.041	8.10E-4	**4.38**
	Biogas from Cattle Dung	-	-	-	0.210	**0.210**
	Biomass Pellets	-	0.209	-	0.092	**0.302**
POFP - Photochemical Oxidant Formation (kg NMVOC)	Hard Coal	0.141	-	0.012	7.71	**7.87**
	Dung Cake	-	-	-	18.8	**18.8**
	Crop Residue	-	-	-	8.22	**8.22**
	Firewood	-	-	-	5.38	**5.38**
	Charcoal from Wood	-	5.30	0.000	5.05	**10.4**
	Kerosene	0.028	0.187	0.112	0.154	**0.481**
	LPG	0.024	0.135	0.108	0.074	**0.341**
	Natural Gas	1.40E-4	0.018	4.74E-3	0.023	**0.046**
	Electricity	-	-	-	2.66	**2.66**
	Sugarcane Ethanol	0.233	0.132	0.150	0.118	**0.633**
	Biogas from Cattle Dung	-	3.59E-3	-	0.110	**0.114**
	Biomass Pellets	-	0.302	-	1.218	**1.520**
FEP - Freshwater Eutrophication (kg P eq)	Hard Coal	8.67E-6	-	1.37E-3	9.91E-4	**2.37E-3**
	Dung Cake	-	-	-	0.189	**0.189**
	Crop Residue	-	-	-	9.80E-3	**9.80E-3**
	Firewood	-	-	-	7.36E-3	**7.36E-3**
	Charcoal from Wood	-	6.35E-3	0.00E+0	7.56E-3	**0.014**
	Kerosene	1.73E-5	1.07E-3	2.68E-3	-3.94E-6	**3.77E-3**
	LPG	1.46E-5	7.37E-4	2.62E-3	-	**3.37E-3**
	Natural Gas	8.92E-8	1.11E-5	5.93E-5	-	**7.05E-5**
	Electricity	-	-	-	3.75E-3	**3.75E-3**
	Sugarcane Ethanol	0.029	4.95E-3	3.48E-3	-1.00E-5	**0.038**

Table A-1. Single Fuel LCIA Results by Life Cycle Stage for India[1]

per GJ delivered heat energy		Life Cycle Stage				TOTAL
Impact Category:	Fuel:	Feedstock Production	Fuel Processing	Distribution	Cookstove Use	
	Biogas from Cattle Dung	-	-	-	-	-
	Biomass Pellets	-	0.005	-	2.50E-4	**0.006**
TAP - Terrestrial Acidification (kg SO2 eq)	Hard Coal	0.076	-	0.011	1.78	**1.87**
	Dung Cake	-	-	-	0.736	**0.736**
	Crop Residue	-	-	-	0.598	**0.598**
	Firewood	-	-	-	0.377	**0.377**
	Charcoal from Wood	-	4.59E-3	0.000	0.205	**0.209**
	Kerosene	0.021	0.168	0.075	0.027	**0.291**
	LPG	0.018	0.153	0.071	0.014	**0.256**
	Natural Gas	1.10E-4	0.013	2.65E-3	0.010	**0.027**
	Electricity	-	-	-	4.54	**4.54**
	Sugarcane Ethanol	3.94	0.322	0.090	-	**4.35**
	Biogas from Cattle Dung	-	-	-	0.106	**0.106**
	Biomass Pellets	-	0.496	-	0.006	**0.502**
ODP - Ozone Depletion (kg CFC-11 eq)	Hard Coal	1.20E-10	-	1.70E-8	1.30E-8	**3.01E-8**
	Dung Cake	-	-	-	1.40E-9	**1.40E-9**
	Crop Residue	-	-	-	7.28E-11	**7.28E-11**
	Firewood	-	-	-	5.46E-11	**5.46E-11**
	Charcoal from Wood	-	4.71E-11	0.00E+0	5.62E-11	**1.03E-10**
	Kerosene	1.06E-9	1.41E-8	4.68E-8	-1.40E-15	**6.20E-8**
	LPG	8.98E-10	2.02E-8	4.45E-8	-6.90E-14	**6.56E-8**
	Natural Gas	5.48E-12	6.88E-10	7.18E-8	-	**7.25E-8**
	Electricity	-	-	-	4.24E-7	**4.24E-7**
	Sugarcane Ethanol	2.65E-6	1.15E-7	6.22E-8	-5.40E-12	**2.82E-6**
	Biogas from Cattle Dung	-	-	-	-	**-**
	Biomass Pellets	-	5.30E-8	-	2.00E-12	**5.31E-8**
Black Carbon and Short-Lived Climate Pollutants (kg BC eq)	Hard Coal	0.345	-	1.10E-4	3.75	**4.10**
	Dung Cake	-	-	-	5.27	**5.27**
	Crop Residue	-	-	-	2.48	**2.48**
	Firewood	-	-	-	1.22	**1.22**
	Charcoal from Wood	-	4.10	0.00E+0	0.479	**4.58**
	Kerosene	7.33E-4	8.93E-3	1.37E-3	0.010	**0.021**
	LPG	6.13E-4	4.18E-3	1.29E-3	5.92E-3	**0.012**
	Natural Gas	3.79E-6	4.56E-4	4.00E-5	1.57E-3	**2.07E-3**
	Electricity	-	-	-	-0.016	**-0.016**
	Sugarcane Ethanol	0.764	-0.014	2.05E-3	5.34E-3	**0.757**
	Biogas from Cattle Dung	-	-	-	0.035	**0.035**
	Biomass Pellets	-	-1.58E-3	-	0.028	**0.026**

[1] LCA results presented in this table are calculated as part of this study based on the methodology described in the report body.

Table A-2. Single Fuel LCIA Results by Life Cycle Stage for China[1]

per GJ delivered heat energy		Life Cycle Stage				
Impact Category:	*Fuel:*	**Feedstock Production**	**Fuel Processing**	**Distribution**	**Cookstove Use**	**TOTAL**
GCCP100 - Climate Change (kg CO2 eq)	Coal Mix	222	14.3	10.5	616	**862**
	Coal Powder	260	-	17.4	888	**1.16E+3**
	Coal Briquettes	191	29.8	3.79	368	**593**
	Coal Honeycomb	176	27.5	3.49	319	**527**
	Firewood	-	-	-	190	**190**
	Crop Residue	-	-	-	64.1	**64.1**
	Kerosene	27.1	19.9	16.4	161	**225**
	Biomass Pellets	-	62.3	-	77.5	**140**
	Electricity	-	-	-	612	**612**
	LPG	24.0	24.8	15.9	148	**213**
	Natural Gas	9.25	-	32.8	112	**154**
	Coal Gas	90.8	30.0	41.0	92.5	**254**
	Sugarcane Ethanol	94.4	13.7	4.02	0.956	**113**
	Biogas from Cattle Dung	-	8.99	-	2.42	**11.4**
CED - Energy Demand (MJ)	Coal Mix	1.34E+3	547	184	6.27E+3	**8.34E+3**
	Coal Powder	1.72E+3	-	307	8.78E+3	**1.08E+4**
	Coal Briquettes	865	1.14E+3	62.7	3.31E+3	**5.37E+3**
	Coal Honeycomb	1.05E+3	1.05E+3	57.8	4.22E+3	**6.37E+3**
	Firewood	-	-	-	7.61E+3	**7.61E+3**
	Crop Residue	-	-	-	7.45E+3	**7.45E+3**
	Kerosene	461	283	262	2.52E+3	**3.53E+3**
	Biomass Pellets	-	900	-	2.88E+3	**3.78E+3**
	Electricity	-	-	-	7.22E+3	**7.22E+3**
	LPG	409	348	357	2.30E+3	**3.41E+3**
	Natural Gas	75.8	-	360	1.93E+3	**2.37E+3**
	Coal Gas	602	177	523	2.39E+3	**3.69E+3**
	Sugarcane Ethanol	2.38E+3	8.62E+3	55.7	2.08E+3	**1.31E+4**
	Biogas from Cattle Dung	-	2.11E+3	-	1.95E+3	**4.06E+3**
FDP - Fossil Depletion (kg oil eq)	Coal Mix	31.8	11.5	2.99	150	**196**
	Coal Powder	40.1	-	4.74	210	**254**
	Coal Briquettes	21.2	23.9	1.29	78.9	**125**
	Coal Honeycomb	25.5	22.0	1.19	101	**149**
	Firewood	-	-	-	3.63E-3	**3.63E-3**
	Crop Residue	-	-	-	0.010	**0.010**
	Kerosene	8.70	5.76	5.26	57.2	**76.9**
	Biomass Pellets	-	12.26	-	1.90E-4	**12.26**
	Electricity	-	-	-	118	**118**
	LPG	7.70	7.16	7.33	52.2	**74.4**
	Natural Gas	1.50	-	7.64	46.1	**55.3**
	Coal Gas	14.0	2.81	11.2	54.2	**82.3**
	Sugarcane Ethanol	16.9	6.74	1.19	-	**24.9**
	Biogas from Cattle Dung	-	-	-	-	**-**
	Coal Mix	0.860	0.095	0.078	0.016	**1.05**

Table A-2. Single Fuel LCIA Results by Life Cycle Stage for China[1]

per GJ delivered heat energy		Life Cycle Stage				
Impact Category:	*Fuel:*	**Feedstock Production**	**Fuel Processing**	**Distribution**	**Cookstove Use**	**TOTAL**
WDP - Water Depletion (m3)	Coal Powder	1.01	-	0.139	8.64E-3	**1.15**
	Coal Briquettes	0.742	0.197	0.017	0.030	**0.986**
	Coal Honeycomb	0.684	0.182	0.016	0.017	**0.899**
	Firewood	-	-	-	4.00E-5	**4.00E-5**
	Crop Residue	-	-	-	1.18E-4	**1.18E-4**
	Kerosene	0.267	0.134	0.079	-	**0.480**
	Biomass Pellets	-	0.417	-	1.00E-5	**0.417**
	Electricity	-	-	-	4.07	**4.07**
	LPG	0.256	0.125	0.080	-	**0.461**
	Natural Gas	0.012	-	0.013	-	**0.025**
	Coal Gas	0.352	0.208	0.016	-	**0.576**
	Sugarcane Ethanol	642	0.987	0.013	-	**643**
	Biogas from Cattle Dung	-	1.02	-	-	**1.02**
PMFP - Particulate Matter Formation (kg PM10 eq)	Coal Mix	0.194	0.139	0.026	10.9	**11.2**
	Coal Powder	0.228	-	0.042	21.2	**21.5**
	Coal Briquettes	0.168	0.289	9.68E-3	0.522	**0.989**
	Coal Honeycomb	0.155	0.267	8.92E-3	0.648	**1.08**
	Firewood	-	-	-	6.50	**6.50**
	Crop Residue	-	-	-	10.0	**10.0**
	Kerosene	0.157	0.058	0.034	0.017	**0.266**
	Biomass Pellets	-	0.168	-	0.143	**0.311**
	Electricity	-	-	-	1.65	**1.65**
	LPG	0.148	0.058	0.033	9.06E-3	**0.248**
	Natural Gas	0.019	-	0.018	0.011	**0.048**
	Coal Gas	0.080	0.346	0.023	0.046	**0.495**
	Sugarcane Ethanol	4.24	0.080	0.013	8.10E-4	**4.33**
	Biogas from Cattle Dung	-	-	-	0.210	**0.210**
POFP - Photochemical Oxidant Formation (kg NMVOC)	Coal Mix	0.178	0.078	0.070	1.95	**2.28**
	Coal Powder	0.208	-	0.106	2.99	**3.30**
	Coal Briquettes	0.154	0.162	0.036	0.349	**0.700**
	Coal Honeycomb	0.142	0.149	0.033	1.49	**1.82**
	Firewood	-	-	-	2.23	**2.23**
	Crop Residue	-	-	-	5.52	**5.52**
	Kerosene	0.250	0.098	0.115	0.120	**0.582**
	Biomass Pellets	-	0.244	-	1.096	**1.340**
	Electricity	-	-	-	2.31	**2.31**
	LPG	0.236	0.094	0.123	0.047	**0.500**
	Natural Gas	0.075	-	0.083	0.023	**0.181**
	Coal Gas	0.073	1.04	0.103	0.096	**1.31**
	Sugarcane Ethanol	0.213	0.132	0.049	0.118	**0.511**
	Biogas from Cattle Dung	-	3.59E-3	-	0.110	**0.114**
FEP - Freshwater	Coal Mix	0.091	5.30E-3	4.56E-3	2.42E-4	**0.102**
	Coal Powder	0.107	-	8.54E-3	1.32E-4	**0.116**

Table A-2. Single Fuel LCIA Results by Life Cycle Stage for China[1]

per GJ delivered heat energy		*Life Cycle Stage*				
Impact Category:	*Fuel:*	**Feedstock Production**	**Fuel Processing**	**Distribution**	**Cookstove Use**	**TOTAL**
Eutrophication (kg P eq)	Coal Briquettes	0.079	0.011	6.10E-4	4.50E-4	**0.091**
	Coal Honeycomb	0.073	0.010	5.68E-4	2.54E-4	**0.084**
	Firewood	-	-	-	4.50E-3	**4.50E-3**
	Crop Residue	-	-	-	0.013	**0.013**
	Kerosene	6.89E-3	3.48E-3	2.44E-3	-	**0.013**
	Biomass Pellets	-	0.012	-	2.40E-4	**0.012**
	Electricity	-	-	-	0.078	**0.078**
	LPG	7.01E-3	2.62E-3	2.79E-3	-1.00E-5	**0.012**
	Natural Gas	2.90E-4	-	3.90E-4	-	**6.80E-4**
	Coal Gas	0.037	4.13E-3	4.90E-4	-	**0.042**
	Sugarcane Ethanol	0.033	4.95E-3	5.00E-4	-	**0.039**
	Biogas from Cattle Dung	-	-	-	-	**-**
TAP - Terrestrial Acidification (kg SO2 eq)	Coal Mix	0.891	0.106	0.063	0.333	**1.39**
	Coal Powder	1.04	-	0.105	0.514	**1.66**
	Coal Briquettes	0.769	0.221	0.022	0.184	**1.20**
	Coal Honeycomb	0.709	0.203	0.020	0.120	**1.05**
	Firewood	-	-	-	0.242	**0.242**
	Crop Residue	-	-	-	0.367	**0.367**
	Kerosene	0.644	0.199	0.088	0.029	**0.960**
	Biomass Pellets	-	0.532	-	0.003	**0.535**
	Electricity	-	-	-	5.27	**5.27**
	LPG	0.604	0.200	0.080	0.014	**0.898**
	Natural Gas	0.082	-	0.051	0.010	**0.143**
	Coal Gas	0.365	0.242	0.063	0.133	**0.803**
	Sugarcane Ethanol	3.97	0.322	0.031	-	**4.33**
	Biogas from Cattle Dung	-	-	-	0.106	**0.106**
ODP - Ozone Depletion (kg CFC-11 eq)	Coal Mix	8.13E-9	4.98E-8	5.59E-8	3.14E-9	**1.17E-7**
	Coal Powder	9.52E-9	-	1.02E-7	1.71E-9	**1.13E-7**
	Coal Briquettes	7.01E-9	1.04E-7	1.02E-8	5.83E-9	**1.27E-7**
	Coal Honeycomb	6.47E-9	9.57E-8	9.41E-9	3.32E-9	**1.15E-7**
	Firewood	-	-	-	3.34E-11	**3.34E-11**
	Crop Residue	-	-	-	9.52E-11	**9.52E-11**
	Kerosene	1.00E-7	4.55E-8	3.91E-8	5.22E-13	**1.85E-7**
	Biomass Pellets	-	2.54E-8	-	1.80E-12	**2.54E-8**
	Electricity	-	-	-	1.67E-7	**1.67E-7**
	LPG	1.01E-7	3.42E-8	4.58E-8	3.50E-13	**1.81E-7**
	Natural Gas	4.44E-9	-	9.69E-7	-	**9.74E-7**
	Coal Gas	3.33E-9	1.16E-5	2.29E-6	-	**1.39E-5**
	Sugarcane Ethanol	2.63E-6	1.15E-7	6.22E-9	0	**2.75E-6**
	Biogas from Cattle Dung	-	-	-	-	**-**
Black Carbon and Short-	Coal Mix	-0.047	0.020	2.74E-4	2.32	**2.29**
	Coal Powder	-0.055	-	1.63E-4	4.51	**4.45**

Table A-2. Single Fuel LCIA Results by Life Cycle Stage for China[1]

per GJ delivered heat energy		Life Cycle Stage				
Impact Category:	***Fuel:***	**Feedstock Production**	**Fuel Processing**	**Distribution**	**Cookstove Use**	**TOTAL**
Lived Climate Pollutants (kg BC eq)	Coal Briquettes	-0.040	0.041	4.00E-4	0.103	**0.105**
	Coal Honeycomb	-0.037	0.038	3.67E-4	0.159	**0.160**
	Firewood	-	-	-	1.42	**1.42**
	Crop Residue	-	-	-	2.20	**2.20**
	Kerosene	-0.030	-5.05E-3	2.00E-4	2.62E-3	**-0.032**
	Biomass Pellets	-	-0.014	-	0.045	**0.031**
	Electricity	-	-	-	-0.148	**-0.148**
	LPG	-0.027	-6.54E-3	8.30E-4	1.65E-3	**-0.031**
	Natural Gas	-3.57E-3	-	-3.00E-5	1.56E-3	**-2.04E-3**
	Coal Gas	-0.019	0.059	-4.00E-5	-2.15E-3	**0.038**
	Sugarcane Ethanol	0.756	-0.014	3.40E-4	5.33E-3	**0.748**
	Biogas from Cattle Dung	-	-	-	0.035	**0.035**

[1] LCA results presented in this table are calculated as part of this study based on the methodology described in the report body.

Table A-3. Single Fuel LCIA Results by Life Cycle Stage for Kenya[1]

per GJ delivered heat energy		Life Cycle Stage				
Impact Category:	*Fuel:*	**Feedstock Production**	**Fuel Processing**	**Distribution**	**Cookstove Use**	**TOTAL**
GCCP100 - Climate Change (kg CO2 eq)	Firewood	-	-	-	439	**439**
	Charcoal from Wood	-	510	15.4	282	**808**
	Biomass Pellets	-	35.1	-	226	**261**
	Kerosene	53.5	13.0	3.99	152	**223**
	LPG	48.3	11.7	14.9	141	**216**
	Electricity	-	-	-	238	**238**
	Biogas from Cattle Dung	-	11.0	-	2.42	**13.4**
	Sugarcane Ethanol	73.8	13.7	1.56	0.953	**90.0**
CED - Energy Demand (MJ)	Firewood	-	-	-	9.11E+3	**9.11E+3**
	Charcoal from Wood	-	6.28E+3	260	5.63E+3	**1.22E+4**
	Biomass Pellets	-	1104	-	3.11E+3	**4.21E+3**
	Kerosene	740	4.65E+3	75.7	2.49E+3	**7.96E+3**
	LPG	667	4.31E+3	331	2.20E+3	**7.51E+3**
	Electricity	-	-	-	7.40E+3	**7.40E+3**
	Biogas from Cattle Dung	-	2.22E+3	-	1.99E+3	**4.21E+3**
	Sugarcane Ethanol	2.39E+3	8.62E+3	26.0	2.08E+3	**1.31E+4**
FDP - Fossil Depletion (kg oil eq)	Firewood	-	-	-	7.20E-3	**7.20E-3**
	Charcoal from Wood	-	2.00E-3	5.34	5.41E-3	**5.35**
	Biomass Pellets	-	19.4	-	2.10E-4	**19.4**
	Kerosene	14.4	111	1.62	59.5	**186**
	LPG	13.0	103	7.12	52.5	**175**
	Electricity	-	-	-	150	**150**
	Biogas from Cattle Dung	-	-	-	-	**-**
	Sugarcane Ethanol	18.7	6.74	0.565	-	**26.0**
WDP - Water Depletion (m3)	Firewood	-	-	-	7.96E-5	**7.96E-5**
	Charcoal from Wood	-	2.21E-5	0.068	6.04E-5	**0.068**
	Biomass Pellets	-	0.635	-	1.00E-5	**0.635**
	Kerosene	0.799	0.021	0.036	-	**0.856**
	LPG	0.721	0.019	0.076	-1.00E-5	**0.816**
	Electricity	-	-	-	5.58	**5.58**
	Biogas from Cattle Dung	-	3.29	-	-	**3.29**
	Sugarcane Ethanol	642	0.987	6.79E-3	-	**643**
PMFP - Particulate Matter Formation (kg PM10 eq)	Firewood	-	-	-	15.5	**15.5**
	Charcoal from Wood	-	6.97	0.039	1.38	**8.40**
	Biomass Pellets	-	0.060	-	0.092	**0.152**
	Kerosene	0.083	0.093	9.11E-3	0.017	**0.202**
	LPG	0.075	0.084	0.029	9.06E-3	**0.196**
	Electricity	-	-	-	0.331	**0.331**
	Biogas from Cattle Dung	-	-	-	0.187	**0.187**

Table A-3. Single Fuel LCIA Results by Life Cycle Stage for Kenya[1]

per GJ delivered heat energy		***Life Cycle Stage***				
Impact Category:	*Fuel:*	**Feedstock Production**	**Fuel Processing**	**Distribution**	**Cookstove Use**	**TOTAL**
	Sugarcane Ethanol	4.17	0.080	3.81E-3	8.10E-4	**4.25**
POFP - Photochemical Oxidant Formation (kg NMVOC)	Firewood	-	-	-	5.87	**5.87**
	Charcoal from Wood	-	19.5	0.147	3.26	**22.9**
	Biomass Pellets	-	0.250	-	1.218	**1.469**
	Kerosene	0.441	0.241	0.038	0.112	**0.832**
	LPG	0.398	0.218	0.118	0.050	**0.783**
	Electricity	-	-	-	1.46	**1.46**
	Biogas from Cattle Dung	-	4.39E-3	-	0.080	**0.084**
	Sugarcane Ethanol	0.166	0.132	0.015	0.118	**0.431**
FEP - Freshwater Eutrophication (kg P eq)	Firewood	-	-	-	8.92E-3	**8.92E-3**
	Charcoal from Wood	-	2.49E-3	1.61E-3	6.71E-3	**0.011**
	Biomass Pellets	-	5.40E-3	-	2.60E-4	**5.66E-3**
	Kerosene	8.95E-3	6.80E-4	3.25E-4	5.12E-6	**9.96E-3**
	LPG	8.08E-3	6.10E-4	2.00E-3	-	**0.011**
	Electricity	-	-	-	1.85E-3	**1.85E-3**
	Biogas from Cattle Dung	-	-	-	-	**-**
	Sugarcane Ethanol	0.029	4.94E-3	1.50E-4	-	**0.034**
TAP - Terrestrial Acidification (kg SO2 eq)	Firewood	-	-	-	0.226	**0.226**
	Charcoal from Wood	-	0.017	0.085	0.107	**0.208**
	Biomass Pellets	-	0.180	-	0.006	**0.186**
	Kerosene	0.191	0.298	0.022	0.029	**0.540**
	LPG	0.173	0.269	0.069	0.014	**0.524**
	Electricity	-	-	-	1.17	**1.17**
	Biogas from Cattle Dung	-	-	-	5.13E-3	**5.13E-3**
	Sugarcane Ethanol	3.75	0.322	8.61E-3	-	**4.08**
ODP - Ozone Depletion (kg CFC-11 eq)	Firewood	-	-	-	6.62E-11	**6.62E-11**
	Charcoal from Wood	-	1.85E-11	4.76E-8	4.98E-11	**4.77E-8**
	Biomass Pellets	-	2.31E-8	-	1.90E-12	**2.31E-8**
	Kerosene	1.08E-7	1.55E-8	6.71E-9	-2.07E-13	**1.30E-7**
	LPG	9.73E-8	1.40E-8	3.68E-8	7.40E-13	**1.48E-7**
	Electricity	-	-	-	3.08E-8	**3.08E-8**
	Biogas from Cattle Dung	-	-	-	-	**-**
	Sugarcane Ethanol	2.63E-6	1.15E-7	3.07E-9	1.70E-13	**2.74E-6**
Black Carbon and Short-Lived Climate Pollutants (kg BC eq)	Firewood	-	-	-	3.32	**3.32**
	Charcoal from Wood	-	1.68	2.04E-3	0.351	**2.03**
	Biomass Pellets	-	-2.33E-3	-	0.028	**0.026**
	Kerosene	3.60E-3	-6.59E-3	2.95E-4	3.27E-3	**5.70E-4**
	LPG	3.25E-3	-5.95E-3	1.06E-3	1.81E-3	**1.70E-4**
	Electricity	-	-	-	-0.032	**-0.032**

Table A-3. Single Fuel LCIA Results by Life Cycle Stage for Kenya[1]

per GJ delivered heat energy		***Life Cycle Stage***				
Impact Category:	*Fuel:*	**Feedstock Production**	**Fuel Processing**	**Distribution**	**Cookstove Use**	**TOTAL**
	Biogas from Cattle Dung	-	-	-	0.040	**0.040**
	Sugarcane Ethanol	0.763	-0.014	1.70E-4	5.33E-3	**0.755**

[1] LCA results presented in this table are calculated as part of this study based on the methodology described in the report body.

Table A-4. Single Fuel LCIA Results by Life Cycle Stage for Ghana[1]

per GJ delivered heat energy		Life Cycle Stage				
Impact Category:	*Fuel:*	**Feedstock Production**	**Fuel Processing**	**Distribution**	**Cookstove Use**	**TOTAL**
GCCP100 - Climate Change (kg CO2 eq)	Firewood	-	-	-	228	**228**
	Crop Residue	-	-	-	120	**120**
	Charcoal from Wood	-	521	30.4	160	**712**
	Biomass Pellets	-	42.2	-	109	**152**
	Kerosene	129	1.03	0.921	152	**284**
	LPG	117	0.927	14.9	141	**274**
	Electricity	-	-	-	259	**259**
	Sugarcane Ethanol	74.9	13.7	4.67	0.953	**94.3**
	Biogas from Cattle Dung	-	11.0	-	2.42	**13.4**
CED - Energy Demand (MJ)	Firewood	-	-	-	9.20E+3	**9.20E+3**
	Crop Residue	-	-	-	1.04E+4	**1.04E+4**
	Charcoal from Wood	-	8.77E+3	513	6.40E+3	**1.57E+4**
	Biomass Pellets	-	1241	-	3.11E+3	**4.35E+3**
	Kerosene	1.24E+3	4.48E+3	24.6	2.49E+3	**8.24E+3**
	LPG	1.12E+3	4.02E+3	337	2.20E+3	**7.67E+3**
	Electricity	-	-	-	7.94E+3	**7.94E+3**
	Sugarcane Ethanol	2.42E+3	8.62E+3	78.0	2.08E+3	**1.32E+4**
	Biogas from Cattle Dung	-	2.22E+3	-	1.99E+3	**4.21E+3**
FDP - Fossil Depletion (kg oil eq)	Firewood	-	-	-	7.36E-3	**7.36E-3**
	Crop Residue	-	-	-	7.56E-3	**7.56E-3**
	Charcoal from Wood	-	3.07E-3	10.5	7.14E-3	**10.6**
	Biomass Pellets	-	21.2	-	2.10E-4	**21.2**
	Kerosene	26.4	107	0.473	59.5	**193**
	LPG	23.8	95.9	7.23	52.5	**179**
	Electricity	-	-	-	150	**150**
	Sugarcane Ethanol	18.7	6.74	1.70	-	**27.2**
	Biogas from Cattle Dung	-	-	-	-	-
WDP - Water Depletion (m3)	Firewood	-	-	-	8.16E-5	**8.16E-5**
	Crop Residue	-	-	-	8.32E-5	**8.32E-5**
	Charcoal from Wood	-	3.38E-5	0.135	7.84E-5	**0.135**
	Biomass Pellets	-	0.868	-	-5.28E-18	**0.868**
	Kerosene	0.045	6.63E-3	0.027	-	**0.078**
	LPG	0.040	5.99E-3	0.081	-	**0.127**
	Electricity	-	-	-	7.58	**7.58**
	Sugarcane Ethanol	643	0.987	0.020	-	**644**
	Biogas from Cattle Dung	-	3.29	-	-	**3.29**
PMFP - Particulate Matter	Firewood	-	-	-	15.5	**15.5**
	Crop Residue	-	-	-	15.4	**15.4**
	Charcoal from Wood	-	8.35	0.077	1.75	**10.2**
	Biomass Pellets	-	0.070	-	0.092	**0.162**

Table A-4. Single Fuel LCIA Results by Life Cycle Stage for Ghana[1]

per GJ delivered heat energy		Life Cycle Stage				
Impact Category:	*Fuel:*	**Feedstock Production**	**Fuel Processing**	**Distribution**	**Cookstove Use**	**TOTAL**
Formation (kg PM10 eq)	Kerosene	0.078	6.15E-3	2.31E-3	0.017	**0.104**
	LPG	0.070	5.55E-3	0.029	9.06E-3	**0.114**
	Electricity	-	-	-	0.310	**0.310**
	Sugarcane Ethanol	4.17	0.080	0.011	8.10E-4	**4.26**
	Biogas from Cattle Dung	-	-	-	0.187	**0.187**
POFP - Photochemical Oxidant Formation (kg NMVOC)	Firewood	-	-	-	5.99	**5.99**
	Crop Residue	-	-	-	9.02	**9.02**
	Charcoal from Wood	-	26.0	0.291	3.80	**30.1**
	Biomass Pellets	-	0.289	-	1.218	**1.508**
	Kerosene	1.33	0.027	9.07E-3	0.111	**1.48**
	LPG	1.20	0.024	0.117	0.050	**1.39**
	Electricity	-	-	-	1.39	**1.39**
	Sugarcane Ethanol	0.162	0.132	0.045	0.118	**0.457**
	Biogas from Cattle Dung	-	4.39E-3	-	0.080	**0.084**
FEP - Freshwater Eutrophication (kg P eq)	Firewood	-	-	-	9.12E-3	**9.12E-3**
	Crop Residue	-	-	-	9.37E-3	**9.37E-3**
	Charcoal from Wood	-	3.81E-3	3.17E-3	8.87E-3	**0.016**
	Biomass Pellets	-	5.88E-3	-	2.60E-4	**6.14E-3**
	Kerosene	1.09E-3	3.50E-4	4.64E-5	3.61E-6	**1.49E-3**
	LPG	9.90E-4	3.10E-4	2.01E-3	-1.00E-5	**3.30E-3**
	Electricity	-	-	-	1.97E-3	**1.97E-3**
	Sugarcane Ethanol	0.029	4.94E-3	4.50E-4	-1.00E-5	**0.034**
	Biogas from Cattle Dung	-	-	-	-	**-**
TAP - Terrestrial Acidification (kg SO2 eq)	Firewood	-	-	-	0.230	**0.230**
	Crop Residue	-	-	-	0.616	**0.616**
	Charcoal from Wood	-	0.055	0.167	0.113	**0.335**
	Biomass Pellets	-	0.200	-	0.006	**0.206**
	Kerosene	0.183	0.019	7.70E-3	0.029	**0.239**
	LPG	0.165	0.017	0.069	0.014	**0.265**
	Electricity	-	-	-	1.10	**1.10**
	Sugarcane Ethanol	3.75	0.322	0.026	-	**4.10**
	Biogas from Cattle Dung	-	-	-	5.13E-3	**5.13E-3**
ODP - Ozone Depletion (kg CFC-11 eq)	Firewood	-	-	-	6.77E-11	**6.77E-11**
	Crop Residue	-	-	-	6.96E-11	**6.96E-11**
	Charcoal from Wood	-	2.83E-11	9.40E-8	6.63E-11	**9.41E-8**
	Biomass Pellets	-	6.83E-8	-	1.90E-12	**6.83E-8**
	Kerosene	1.87E-8	1.08E-8	1.42E-9	6.00E-15	**3.09E-8**
	LPG	1.69E-8	9.73E-9	3.76E-8	-6.00E-14	**6.42E-8**
	Electricity	-	-	-	3.61E-7	**3.61E-7**
	Sugarcane Ethanol	2.64E-6	1.15E-7	9.21E-9	5.00E-13	**2.77E-6**

Table A-4. Single Fuel LCIA Results by Life Cycle Stage for Ghana[1]

per GJ delivered heat energy		***Life Cycle Stage***				**TOTAL**
Impact Category:	*Fuel:*	**Feedstock Production**	**Fuel Processing**	**Distribution**	**Cookstove Use**	
	Biogas from Cattle Dung	-	-	-	-	**-**
Black Carbon and Short-Lived Climate Pollutants (kg BC eq)	Firewood	-	-	-	3.33	**3.33**
	Crop Residue	-	-	-	3.36	**3.36**
	Charcoal from Wood	-	2.05	4.03E-3	0.437	**2.49**
	Biomass Pellets	-	-1.54E-3	-	0.028	**0.026**
	Kerosene	9.43E-3	-2.60E-4	-1.79E-4	3.26E-3	**0.012**
	LPG	8.51E-3	-2.40E-4	1.07E-3	1.81E-3	**0.011**
	Electricity	-	-	-	-0.030	**-0.030**
	Sugarcane Ethanol	0.763	-0.014	5.20E-4	5.33E-3	**0.755**
	Biogas from Cattle Dung	-	-	-	0.040	**0.040**

[1] LCA results presented in this table are calculated as part of this study based on the methodology described in the report body.

Appendix B

Comparison of Results Updates between Phase I and Phase II Study for India and China

Table B-1 includes a comparison of the Phase I and Phase II LCA results for traditional fuels in India. Several study assumptions were modified for the second phase of this work based improved country-specific data, Phase 1 peer review suggestions, and additional stakeholder input. Notes are provided regarding reasons behind the more dramatic changes in estimated impact between the two phases of work:

- Baseline forest renewability factor for Phase II estimates that a higher percentage of forest products are produced using renewable practices, which leads to the assumption that associated CO_2 emissions are carbon neutral, thereby contributing to the observed change in GCCP impact of firewood.
- CED of hard coal drops in Phase II due to a reduction in the estimated embodied energy of coal feedstock at the mine that was implemented to align the background unit process heating value with the country-specific fuel heating value for India (Singh et al. 2014a).
- WDP impacts for the second phase of work are significantly lower than those in Phase I due to implementation of the assumption that hydropower turbine water should not be characterized in estimates of WDP impact because the water is still available for environmental uses, does not leave the waterway, and is therefore not depleted.
- The reduction in PMFP, BC, and POFP emissions for kerosene is due to reduced estimates of use phase emissions as documented in Table 2-1 and SI2.
- The reduction in the charcoal estimated FDP in Phase II is due to the removal of processing energy associated with the assumption that chunk charcoal (i.e., not briquettes) are being used.
- FEP of traditional fuels decreased significantly in Phase II due to a change in the characterization factor used to estimate FEP impact of land applied ash. Only 5%, as opposed to 100%, of land applied phosphorus is now assumed to make its way to local water bodies to contribute to FEP. This assumption is in better alignment with estimates associated with characterization of nutrients contained in land applied manure (Goedkoop et al. 2008).
- ODP results have dropped significantly in Phase II resulting from the replacement of HCFC 1211 and Halon 1301 with HCFC-123 and HFC-227ea, respectively.

Table B-1. Comparison on Phase I and Phase II LCA Results, Traditional Fuels, India[4]

Impact Category	Value Description	Hard Coal	Dung Cake	Crop Residue	Firewood	Kerosene	Charcoal
GCCP100 - Climate Change (kg CO_2 eq)	Phase II Result	963	263	119	196	181	402
	Phase I Result	963	191	132	539	181	572
	Percent Change[1]	0%	28%	-11%	-174%	0%	-42%

Table B-1. Comparison on Phase I and Phase II LCA Results, Traditional Fuels, India[4]

Impact Category	Value Description	Hard Coal	Dung Cake	Crop Residue	Firewood	Kerosene	Charcoal
Energy Demand - CED (MJ)	Phase II Result	7.21E+03	1.30E+04	1.01E+04	6.52E+03	3.09E+03	1.09E+04
	Phase I Result	1.40E+04	1.30E+04	9.70E+03	7.70E+03	2.60E+03	1.00E+04
	Percent Change	-94%	0%	4%	-18%	16%	8%
FDP - Fossil depletion (kg oil eq)	Phase II Result	172	0.152	7.90E-03	5.90E-03	71	0.011
	Phase I Result	243	0.155	7.60E-03	6.40E-03	65.7	0.117
	Percent Change	-41%	-2%	4%	-7%	7%	-944%
WDP - Water depletion (m^3)	Phase II Result	0.397	1.68E-03	8.72E-05	6.54E-05	0.239	1.20E-04
	Phase I Result	16.6	1.19	0.058	0.049	36.3	0.629
	Percent Change	n.a.[2]	n.a.[2]	n.a.[2]	n.a.[2]	n.a.[2]	n.a.[2]
PMFP - Particulate matter formation (kg PM_{10} eq)	Phase II Result	19.8	24.3	11.4	5.54	0.171	20.5
	Phase I Result	19.3	23.6	11.3	4.72	0.308	19.5
	Percent Change	2%	3%	1%	15%	-80%	5%
POFP - Photochemical oxidant formation (kg NMVOC)	Phase II Result	7.87	18.8	8.22	5.38	0.483	10.4
	Phase I Result	7.86	18.7	8.75	6.02	1.16	10.5
	Percent Change	0%	1%	-7%	-12%	-140%	-1%
FEP - Freshwater eutrophication (kg P eq)	Phase II Result	2.37E-03	0.188586	9.80E-03	7.36E-03	3.79E-03	0.014
	Phase I Result	2.10E-03	3.82	0.187	0.157	3.30E-03	0.278
	Percent Change	11%	n.a.[3]	n.a.[3]	n.a.[3]	13%	n.a.[3]
TAP - Terrestrial acidification (kg SO_2 eq)	Phase II Result	1.87	0.736	0.598	0.377	0.292	0.209
	Phase I Result	1.87	0.749	0.616	0.4	0.398	0.209
	Percent Change	0%	-2%	-3%	-6%	-36%	0%
ODP - Ozone depletion (kg CFC-11 eq)	Phase II Result	3.01E-08	1.40E-09	7.28E-11	5.46E-11	6.20E-08	1.03E-10
	Phase I Result	8.20E-07	6.20E-08	3.10E-09	2.60E-09	2.40E-06	4.50E-09
	Percent Change	-2626%	-4328%	-4161%	-4658%	-3772%	-4257%
Black Carbon and Short-Lived Climate Pollutants (kg BC eq)	Phase II Result	4.1	5.27	2.48	1.22	0.021	4.58
	Phase I Result	3.91	5.01	2.42	1.04	0.045	4.27
	Percent Change	4%	5%	2%	14%	-112%	7%

[1] Percent change calculated as (Phase II Value-Phase I Value)/Phase II Value.
[2] Removal of turbine water changes basis of impact category from water consumption to water depletion.
[3] Change in the characterization factor associated with land application of ash residue reduces impact by a factor of 20.
[4] LCA results presented in this table are calculated as part of this study based on the methodology described in the report body.

Table B-2 includes a comparison of the Phase I and Phase II LCA results for modern cooking fuels in India. Several study assumptions were modified for the second phase of this work based improved country-specific data, Phase 1 peer review suggestions, and additional stakeholder input. Notes are provided regarding reasons behind the more dramatic changes in estimated impact between the two phases of work:

- The reduction in LPG GCCP and POFP is due to lower estimates of use phase emissions.
- WDP impacts for the second phase of work are significantly lower than the WDP impacts in Phase I due to implementation of the assumption that hydropower turbine water should not be characterized in estimates of WDP impact, because the water is still available for environmental uses, does not leave the waterway, and is therefore not depleted.
- The increase in biomass pellet eutrophication potential is attributable to wood ash (waste disposal) during the pelletization process.
- Increases in impact associated with sugarcane ethanol are generally attributable to impacts associated with agricultural production of sugarcane. New unit processes based on the latest research representing Indian sugarcane production have been developed for Phase II.
- ODP results have dropped significantly in Phase II resulting from the replacement of HCFC 1211 and Halon 1301 with HCFC-123 and HFC-227ea, respectively.

Table B-2. Comparison of Phase I and Phase II LCA Results, Modern Fuels, India[4]

Impact Category	Value Description	LPG	Natural Gas	Electricity	Sugarcane Ethanol	Biogas	Biomass Pellets
GCCP100 - Climate Change (kg CO_2 eq)	Phase II Result	157	117	457	121	11.4	141
	Phase I Result	297	-	415	95.7	10.5	134
	Percent Change[2]	-89%	n.a.[1]	9%	21%	8%	5%
Energy Demand - CED (MJ)	Phase II Result	2.61E+03	2.04E+03	5.70E+03	1.33E+04	4.06E+03	3.91E+03
	Phase I Result	1.70E+03	-	5.40E+03	6.50E+03	1.80E+03	2.00E+03
	Percent Change	35%	n.a.[1]	5%	51%	56%	49%
FDP - Fossil depletion (kg oil eq)	Phase II Result	58.7	48.7	122	31	-	13.7
	Phase I Result	44.9	-	91.4	18.3	-	6.25
	Percent Change	24%	n.a.[1]	25%	41%	0%	54%
WDP - Water depletion (m^3)	Phase II Result	0.193	0.039	3.25	643	1.02	0.357
	Phase I Result	29.2	-	515	88.6	1.04	35.6
	Percent Change	n.a.[3]	n.a.[1]	n.a.[3]	n.a.[3]	n.a.[3]	n.a.[3]
PMFP - Particulate matter formation (kg PM_{10} eq)	Phase II Result	0.136	0.019	1.91	4.38	0.21	0.302
	Phase I Result	0.142	-	1.69	0.167	0.077	0.212
	Percent Change	-4%	n.a.[1]	12%	96%	63%	30%
POFP - Photochemical oxidant	Phase II Result	0.341	0.046	2.66	0.633	0.114	1.52
	Phase I Result	0.687	-	2.01	0.342	0.114	0.237

Table B-2. Comparison of Phase I and Phase II LCA Results, Modern Fuels, India[4]

Impact Category	Value Description	LPG	Natural Gas	Electricity	Sugarcane Ethanol	Biogas	Biomass Pellets
formation (kg NMVOC)	Percent Change	-102%	n.a.[1]	24%	46%	0%	84%
FEP - Freshwater eutrophication (kg P eq)	Phase II Result	3.37E-03	7.05E-05	3.75E-03	0.0375	0	0.006
	Phase I Result	2.50E-03	-	3.40E-03	0.037	0	3.40E-03
	Percent Change	26%	n.a.[1]	9%	1%	0%	38%
TAP - Terrestrial acidification (kg SO_2 eq)	Phase II Result	0.256	0.027	4.54	4.35	0.106	0.502
	Phase I Result	0.316	-	4	0.498	0.106	0.291
	Percent Change	-24%	n.a.[1]	12%	89%	0%	42%
ODP - Ozone depletion (kg CFC-11 eq)	Phase II Result	6.56E-08	7.25E-08	4.24E-07	2.82E-06	0.00E+00	5.31E-08
	Phase I Result	2.10E-06	0.00E+00	1.40E-06	6.30E-06	0.00E+00	3.20E-07
	Percent Change	-3101%	n.a.[1]	-230%	-123%	0%	-503%
Black Carbon and Short-Lived Climate Pollutants (kg BC eq)	Phase II Result	0.012	2.10E-03	-0.016	0.757	0.035	0.026
	Phase I Result	7.30E-03	-	-0.019	-5.40E-03	6.80E-03	0.02
	Percent Change	39%	n.a.[1]	-15%	101%	81%	24%

[1] Not applicable due to the absence of natural gas in Phase I.
[2] Percent change calculated as (Phase II Value-Phase I Value)/Phase II Value.
[3] Removal of turbine water changes basis of impact category from water consumption to water depletion.
[4] LCA results presented in this table are calculated as part of this study based on the methodology described in the report body.

Table B-3 includes a comparison of the Phase I and Phase II LCA results for traditional fuels in China. Several study assumptions were modified for the second phase of this work based improved country-specific data, Phase 1 peer review suggestions, and additional stakeholder input. Notes are provided regarding reasons behind the more dramatic changes in estimated impact between the two phases of work:

- Baseline forest renewability factor for Phase II estimates that a higher percentage of forest products are produced using renewable practices, which leads to the assumption that associated CO_2 emissions are carbon neutral, thereby contributing to the observed change in GCCP impact of firewood.

- CED of coal briquettes drops in Phase II due to a reduction in the estimated embodied energy of coal feedstock at the mine that was implemented to align the background unit process heating value with the country specific, fuel heating value for China (Zhang et al. 2000).

- WDP impacts for the second phase of work are significantly lower than the WDP impacts in Phase I due to implementation of the assumption that hydropower turbine water should not be characterized in estimates of WDP impact because the water is still available for environmental uses, does not leave the waterway, and is therefore not depleted.

- PMFP and BC impacts of coal feedstock increase significantly due to the inclusion of PM>2.5 in the Phase II emissions inventory. The value for coal cookstoves is used as a proxy (Singh et al. 2014a) and is linearly scaled based on the difference in thermal efficiency between the cookstove from the original source and the stove type in China.

- The reduction in TAP for coal powder is due to a reduced estimate of use phase emissions due to the use of the geometric mean as the analysis value in Phase II of the study as opposed to the arithmetic mean. The difference in the two means is significant for SO_2 emissions due to the high standard deviation of the reported SO_2 emissions.

- ODP results have dropped significantly in Phase II resulting from the replacement of HCFC 1211 and Halon 1301 with HCFC-123 and HFC-227ea, respectively.

Table B-3. Comparison of Phase I and Phase II LCA Results, Traditional Fuels, China[4]

Impact Category	Value Description	Coal Mix	Coal Powder	Coal Briquettes	Coal Honeycomb	Firewood	Crop Residue	Kerosene
GCCP100 - Climate Change (kg CO_2 eq)	Phase II Result	862	1.16E+03	593	527	190	64.1	225
	Phase I Result	1.01E+03	1.29E+03	784	695	281	54.7	207
	Percent Change[1]	-18%	-11%	-32%	-32%	-48%	15%	8%
Energy Demand - CED (MJ)	Phase II Result	8.35E+03	1.08E+04	5.37E+03	6.37E+03	7.61E+03	7.45E+03	3.53E+03
	Phase I Result	1.10E+04	1.30E+04	8.90E+03	7.60E+03	6.50E+03	7.90E+03	2.90E+03
	Percent Change	-32%	-20%	-66%	-19%	15%	-6%	18%
FDP - Fossil depletion (kg oil eq)	Phase II Result	195	253	125	149	3.63E-03	0.01	76.9
	Phase I Result	179	213	158	134	2.45E-03	0.015	67.7
	Percent Change	8%	16%	-26%	11%	32%	-49%	12%
WDP - Water depletion (m^3)	Phase II Result	1.05	1.15	0.986	0.899	4.00E-05	1.20E-04	0.48
	Phase I Result	44.5	19.1	76.3	63.7	0.019	0.118	72.3
	Percent Change	n.a.[2]	n.a.[2]	n.a.[2]	n.a.[2]	n.a.[2]	n.a.[2]	n.a.[2]
PMFP - Particulate matter formation (kg PM_{10} eq)	Phase II Result	11.2	21.5	0.989	1.08	6.5	10	0.266
	Phase I Result	1.81	2.96	0.68	0.631	1.49	3.4	0.232
	Percent Change	84%	86%	31%	41%	77%	66%	13%
POFP - Photochemical oxidant formation (kg NMVOC)	Phase II Result	2.28	3.3	0.7	1.82	2.23	5.52	0.582
	Phase I Result	2.33	3.31	1.2	1.5	1.81	2.52	0.425
	Percent Change	-2%	0%	-71%	17%	19%	54%	27%
FEP - Freshwater	Phase II Result	0.102	0.116	0.091	0.084	4.50E-03	0.013	0.013

Table B-3. Comparison of Phase I and Phase II LCA Results, Traditional Fuels, China[4]

Impact Category	Value Description	Coal Mix	Coal Powder	Coal Briquettes	Coal Honeycomb	Firewood	Crop Residue	Kerosene
eutrophication (kg P eq)	Phase I Result	0.11	0.137	0.089	0.076	0.061	0.38	0.01
	Percent Change	-8%	-18%	2%	10%	n.a.[3]	n.a.[3]	19%
TAP - Terrestrial acidification (kg SO_2 eq)	Phase II Result	1.39	1.66	1.2	1.05	0.242	0.367	0.96
	Phase I Result	3.72	5.94	1.6	1.42	0.289	0.301	0.867
	Percent Change	-167%	-257%	-34%	-35%	-19%	18%	10%
ODP - Ozone depletion (kg CFC-11 eq)	Phase II Result	1.17E-07	1.13E-07	1.27E-07	1.15E-07	3.34E-11	9.52E-11	1.85E-07
	Phase I Result	6.40E-06	8.40E-07	1.30E-05	1.10E-05	9.90E-10	6.20E-09	3.80E-05
	Percent Change	-5369%	-642%	-10154%	-9477%	-2862%	-6412%	-20464%
Black Carbon and Short-Lived Climate Pollutants (kg BC eq)	Phase II Result	2.29	4.45	0.105	0.16	1.42	2.2	-0.032
	Phase I Result	0.043	0.041	0.047	0.044	0.298	0.693	-0.032
	Percent Change	98%	99%	55%	73%	79%	69%	1%

[1] Percent change calculated as (Phase II Value-Phase I Value)/Phase II Value.
[2] Removal of turbine water changes basis of impact category from water consumption to water depletion.
[3] Change in the characterization factor associated with land application of ash residue reduces impact by a factor of 20.
[4] LCA results presented in this table are calculated as part of this study based on the methodology described in the report body.

Table B-4 includes a comparison of the Phase I and Phase II LCA results for modern fuels in China. Several study assumptions were modified for the second phase of this work based improved country-specific data, Phase 1 peer review suggestions, and additional stakeholder input. Notes are provided regarding reasons behind the more dramatic changes in estimated impact between the two phases of work:

- Sugarcane ethanol, biogas, and coal gas were not included in Phase I for China, and so the percent change has not been calculated.
- WDP impacts for the second phase of work are significantly lower than the WDP impacts in Phase I due to implementation of the assumption that hydropower turbine water should not be characterized in estimates of WDP impact, because the water is still available for environmental uses, does not leave the waterway, and is therefore not depleted.
- The increase in the biomass pellet eutrophication potential is attributable to wood ash (waste disposal) during the pelletization process.
- ODP results have dropped significantly in Phase II resulting from the replacement of HCFC 1211 and Halon 1301 with HCFC-123 and HFC-227ea, respectively.
- The decrease in BC impact score for LPG is associated with crude oil production.

- Coal gas replaced the proposed use of dimethyl ether (DME) in the Phase II study based on references that demonstrate current use of coal gas (World Bank 2008, Mainali et al 2012), and the predicted increase in coal gas use predicted by Mainali et al. (2012). Additionally, the LCI data used for DME in Phase I was adapted from information initially pertaining to coal gas. Inclusion of coal gas in Phase II prevents the need for this adaptation.

Table B-4. Comparison of Phase I and Phase II LCA Results, Modern Fuels, China[4]

Impact Category	Value Description	Biomass Pellets	Electricity	LPG	Natural Gas	Coal Gas	Sugarcane Ethanol	Biogas
GCCP100 - Climate Change (kg CO_2 eq)	Phase II Result	140	612	213	154	254	113	11.4
	Phase I Result	118	496	188	213	-	-	-
	Percent Change[1]	16%	19%	12%	-38%	n.a.[2]	n.a.[2]	n.a.[2]
Energy Demand - CED (MJ)	Phase II Result	3.78E+03	7.22E+03	3.41E+03	2.37E+03	3.69E+03	1.31E+04	4.06E+03
	Phase I Result	2.40E+03	6.10E+03	2.80E+03	2.00E+03	-	-	-
	Percent Change	37%	16%	18%	15%	n.a.[2]	n.a.[2]	n.a.[2]
FDP - Fossil depletion (kg oil eq)	Phase II Result	12.3	118	74.4	55.3	82.3	24.9	-
	Phase I Result	8.12	95.6	64.4	48.6	-	-	-
	Percent Change	34%	19%	13%	12%	n.a.[2]	n.a.[2]	n.a.[2]
WDP - Water depletion (m^3)	Phase II Result	0.417	4.07	0.461	0.025	0.576	643	1.02
	Phase I Result	49.2	524	57.1	5.77	-	-	-
	Percent Change	n.a.[3]	n.a.[3]	n.a.[3]	n.a.[3]	n.a.[2]	n.a.[2]	n.a.[2]
PMFP - Particulate matter formation (kg PM_{10} eq)	Phase II Result	0.311	1.65	0.248	0.048	0.495	4.33	0.21
	Phase I Result	0.215	1.33	0.198	0.057	n.a.[1]	n.a.[1]	n.a.[1]
	Percent Change	31%	19%	20%	-19%	n.a.[2]	n.a.[2]	n.a.[2]
POFP - Photochemical oxidant formation (kg NMVOC)	Phase II Result	1.34	2.31	0.5	0.181	1.31	0.511	0.114
	Phase I Result	0.26	1.87	0.401	0.226	-	-	-
	Percent Change	81%	19%	20%	-24%	n.a.[2]	n.a.[2]	n.a.[2]
FEP - Freshwater eutrophication (kg P eq)	Phase II Result	0.012	0.078	0.012	6.80E-04	0.042	0.039	-
	Phase I Result	0.02	0.063	8.00E-03	6.80E-04	-	-	-
	Percent Change	-65%	19%	35%	-1%	n.a.[2]	n.a.[2]	n.a.[2]

Table B-4. Comparison of Phase I and Phase II LCA Results, Modern Fuels, China[4]

Impact Category	Value Description	Biomass Pellets	Electricity	LPG	Natural Gas	Coal Gas	Sugarcane Ethanol	Biogas
TAP - Terrestrial acidification (kg SO_2 eq)	Phase II Result	0.535	5.27	0.898	0.143	0.803	4.33	0.106
	Phase I Result	0.392	4.27	0.683	0.17	-	-	-
	Percent Change	27%	19%	24%	-19%	n.a.[2]	n.a.[2]	n.a.[2]
ODP - Ozone depletion (kg CFC-11 eq)	Phase II Result	2.54E-08	1.67E-07	1.81E-07	9.74E-07	1.39E-05	2.75E-06	0
	Phase I Result	2.30E-07	2.30E-06	2.90E-05	3.40E-05	-	-	-
	Percent Change	-807%	-1275%	-15898%	-3391%	n.a.[2]	n.a.[2]	n.a.[2]
Black Carbon and Short-Lived Climate Pollutants (kg BC eq)	Phase II Result	0.031	-0.148	-0.031	-2.00E-03	0.038	0.748	0.035
	Phase I Result	0.011	-0.121	-0.018	-2.20E-03	-	-	-
	Percent Change	64%	18%	42%	-7%	n.a.[2]	n.a.[2]	n.a.[2]

[1] Percent change calculated as (Phase II Value-Phase I Value)/Phase II Value.
[2] Not applicable due to absence of fuel in Phase I work.
[3] Removal of turbine water changes basis of impact category from water consumption to water depletion.
[4] LCA results presented in this table are calculated as part of this study based on the methodology described in the report body.

Appendix C
Data Quality

A general introduction to data quality criteria and assessment is presented in Section 1.4 of the main report. Results of the data quality evaluation are catalogued in Table C-1 through Table C-4. Data quality cannot be assessed using the exact same data quality metrics for all types of data used in this project. The following list of data quality considerations provides specific interpretations of the generalized Data Quality Rubric presented in Table 1-5 for the main data sources used in this project.

Additional data quality information is provided in the SI files.

- **Cooking Fuel Mix**
  - Data quality is only assessed for Current and BAU Scenarios. Other scenarios are included as a form of sensitivity analysis. Actual likelihood of cooking fuel mix adoption at a future date in line with these scenarios should be assessed based on the rationale described in the main report and in SI3 for each cooking fuel mix.
  - *Data Source Reliability* – This quality criterion is used to evaluate the institution/publication and the methods used to estimate the future cooking fuel mix. Standard rubric criteria and interpretation apply.
  - *Data Completeness* – Assesses how well the information is expected to represent the national cooking fuel mix.
  - *Temporal Correlation* – The quality of current cooking fuel mix estimates is very sensitive to the age of the associated data. The temporal correlation of future cooking fuel mixes is not estimated. While some of the information on which future cooking fuel mix estimates are made pertain to a specific year (e.g., 2030) this study does not intend to project the future cooking fuel mix at a given point in the future. The study rather provides a range of potential cooking fuel mix estimates as part of the sensitivity analysis.
  - *Technological Correlation* – Standard rubric criteria and interpretation apply. All information meets the highest quality criterion.
  - *Geographic Correlation* – Geographic correlation is considered on a restricted scale. Only values of ‘High’ or ‘Medium Low’ are assigned. Medium Low geographic data quality represents data that are “Data from area with slightly similar production conditions.” Given that technology and fuel type are fixed, this is estimated to be a conservative estimate of data quality that would reflect differences in crop/wood type or climate that have an impact on stove performance.

- **Stove Technology Mix**
  - *Data Source Reliability* – This quality criterion is used to evaluate the institution and publication and the methods with which they provide information pertaining to the stove technology mix.
  - *Data Completeness* – Assesses how well the information is expected to represent the national cookstove technology use.

- *Temporal Correlation* – The quality of cookstove technology mix estimates is very sensitive to the age of the associated data. Standard rubric criteria and interpretation apply.
- *Technological Correlation* – All information pertaining to the stove technology mix is representative of appropriate stove-group.
- *Geographic Correlation* – Geographic correlation is considered on a restricted scale. Only values of ‘High’ or ‘Medium Low’ are assigned. Medium Low geographic data quality represents data that are “Data from area with slightly similar production conditions.”

- **Stove Group LCI Data**
  - *Data Source Reliability* – All stove emission data are based on verified measurements.
  - *Data Completeness* – Data completeness is estimated based on the number of stoves for which a given stove group LCI is developed.
  - *High*- Stove LCI values based on records for >10 stoves.
    - *Medium High***-** Stove LCI values based on records for >5 stoves.
    - *Medium*- Stove LCI values based on records for 3-4 stoves.
    - *Medium Low* – Stove LCI values based on records for 2 stoves.
    - *Low* – Stove LCI values based on records for 1 stove.
  - *Temporal Correlation* – Age of stove emissions data is not assumed to be a critical data quality criterion given that the fuel and stove technology are fixed, regardless of year. Combustion process for a given stove-fuel combination are not expected to change over time. Date range of references is noted, but quality estimate is marked with N/A.
  - *Technological Correlation* – The following stove pollutants are considered necessary for a complete use-phase emissions inventory: (1) CO, (2) CO_2, (3) CH_4, (4) N_2O, (5) NO_x, (6) SO_2, (7) PM2.5, (8) PM>2.5<10, and (9) NMVOCs. Technology correlation is assessed based on the number of primary pollutant emission values reported for each specific stove grouping.
    - *High*-Records for all pollutants available for appropriate stove fuel-technology combination.
    - *Medium High***-** Records for six or more pollutants available for appropriate stove fuel-technology combination. Remaining pollutants use proxy value based on similar technology scaled to appropriate stove efficiency.
    - *Medium*- Records for four or five pollutants available for appropriate stove fuel-technology combination. Remaining pollutants use proxy value based on similar technology scaled to appropriate stove efficiency.
    - *Medium Low* – Records for three or less pollutants available for appropriate stove fuel-technology combination. Remaining pollutants use proxy value based on similar technology scaled to appropriate stove efficiency.

    - *Low* – Less than three emission species available for specific stove group. Proxy emission value not available for all pollutants (i.e., missing some pollutant flows).
  - *Geographic Correlation* – Geographic correlation is considered on a restricted scale. Only values of 'High' or 'Medium Low' are assigned. Medium Low geographic data quality represents data that are "Data from area with slightly similar production conditions."

- **Electricity Mix**

  - *Data Source Reliability* – This quality criterion is used to evaluate the institution, publication, and methodology used to estimate the electricity fuel and technology mix.
  - *Data Completeness* – For current electrical mixes standard rubric criteria and interpretation apply. Data completeness is not evaluated for future electrical energy mixes.
  - *Temporal Correlation* – Standard rubric criteria and interpretation apply.
  - *Technological Correlation* – Technological correlation is an important quality criterion for electricity mix information. The sources are largely distinguished on whether they specify the combustion technology used to produce electricity.
  - *Geographic Correlation* – All electricity mix information is based on information related to the specified country.

Table C-1. Cooking Fuel Mix Data Quality Documentation

Data Type	Fuel Mix Name	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
Cooking Fuel Mix	Current	India	**Data Source Reliability**	Based primarily on two sources: 1) an unpublished market report from GACC (a leading organization in the cookstove sector), 2) a published study with data based on a national survey	Medium	Results are primarily based on estimates adapted from Dalberg et al. (2013b). Limited information from on older publication (Venkataraman et al. 2010) is used to break out the charcoal value. Gov of India (2014) provides additional statistics to determine the split between LPG produced from natural gas versus crude oil	SI3
			Data Completeness	Covers all rural and urban households from all regions of India, but data developed from multiple sources	Medium		
			Temporal Correlation	Fuel mix estimates primarily from2013, with limited information from 2007 included, less than 10 years of difference	Medium		
			Geographic Correlation	India	High		
			Technological Correlation	Data from technology, process, or materials being studied	High		
Cooking Fuel Mix	BAU 2040	India	**Data Source Reliability**	IEA Report; Data verified with many assumptions, or non-verified but from quality source	Medium	Good source of information. Future projection by a reputable agency. Better documentation of methods could lead to a higher quality estimate	SI3
			Data Completeness	Representativeness unknown or incomplete data sets	Low		
			Temporal Correlation	Fuel mix estimate for year 2040	N/A		
			Geographic Correlation	India	High		
			Technological Correlation	Data from technology, process, or materials being studied	High		
Cooking Fuel Mix	Improved Biomass	India	**Data Source Reliability**	ERG adaptation of (IEA 2007) 2030 fuel mix projection	N/A	Future cooking fuel mixes are included as part of the sensitivity analysis. See SI3 or additional detail and documentation of sources and assumptions	SI3
			Data Completeness	N/A - sensitivity analysis	N/A		
			Temporal Correlation	N/A - sensitivity analysis	N/A		
			Geographic Correlation	N/A - sensitivity analysis	N/A		
			Technological Correlation	Data from technology, process, or materials being studied	N/A		

Table C-1. Cooking Fuel Mix Data Quality Documentation

Data Type	Fuel Mix Name	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
Cooking Fuel Mix	Increased Electricity	India	**Data Source Reliability**	ERG adaptation of (IEA 2007) 2030 fuel mix projection	N/A	Future cooking fuel mixes are included as part of the sensitivity analysis. See SI3 or additional detail and documentation of sources and assumptions	SI3
			Data Completeness	N/A - sensitivity analysis	N/A		
			Temporal Correlation	N/A - sensitivity analysis	N/A		
			Geographic Correlation	N/A - sensitivity analysis	N/A		
			Technological Correlation	Data from technology, process, or materials being studied	N/A		
Cooking Fuel Mix	Diverse Modern Fuels	India	**Data Source Reliability**	Unqualified estimate based on previous LCA results	N/A	Future cooking fuel mixes are included as part of the sensitivity analysis. See SI3 or additional detail and documentation of sources and assumptions	SI3
			Data Completeness	N/A - sensitivity analysis	N/A		
			Temporal Correlation	N/A - sensitivity analysis	N/A		
			Geographic Correlation	N/A - sensitivity analysis	N/A		
			Technological Correlation	Data from technology, process, or materials being studied	N/A		
Cooking Fuel Mix	Current	China	**Data Source Reliability**	Data largely from a market assessment from GACC that is no longer publicly available, but the data source was originally recommended by GACC, a leading organization in the sector	Medium	Dalberg 2014 is used for the majority of cooking fuel mix assumptions. NBSC 2008 is used to determine specific crop types for the crop residues	SI3
			Data Completeness	Covers rural and urban households based on a survey of a representative sample of the country	Medium		
			Temporal Correlation	Data collection completed in 2013, less than six year of difference	High		
			Geographic Correlation	Covers six provinces in China to be representative of the whole country	Medium		
			Technological Correlation	Data from technology, process, or materials being studied	High		
Cooking Fuel Mix	BAU 2030	China	**Data Source Reliability**	Mainali et al. 2012; data verified with many assumptions, or non-verified but from quality source	Medium		SI3

Table C-1. Cooking Fuel Mix Data Quality Documentation

Data Type	Fuel Mix Name	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Data Completeness	Sufficient number of sites, but a less adequate period of time	Medium		
			Temporal Correlation	Fuel mix estimate for year 2030	N/A		
			Geographic Correlation	China	High		
			Technological Correlation	Data from technology, process, or materials being studied	High		
			Data Source Reliability	ERG adaptation of Mainali et al. 2012/2030 fuel mix	N/A		
			Data Completeness	N/A - sensitivity analysis	N/A		
Cooking Fuel Mix	Increased Electricity	China	**Temporal Correlation**	N/A - sensitivity analysis	N/A	Future cooking fuel mixes are included as part of the sensitivity analysis. See SI3 or additional detail and documentation of sources and assumptions	SI3
			Geographic Correlation	N/A - sensitivity analysis	N/A		
			Technological Correlation	Data from technology, process, or materials being studied	N/A		
			Data Source Reliability	ERG adaptation of Mainali et al. 2012/2030 fuel mix	N/A		
			Data Completeness	N/A - sensitivity analysis	N/A		
Cooking Fuel Mix	Advanced Biomass & Electricity	China	**Temporal Correlation**	N/A - sensitivity analysis	N/A	Future cooking fuel mixes are included as part of the sensitivity analysis. See SI3 or additional detail and documentation of sources and assumptions	SI3
			Geographic Correlation	N/A - sensitivity analysis	N/A		
			Technological Correlation	Data from technology, process, or materials being studied	N/A		
			Data Source Reliability	Unqualified estimate based on previous LCA results	N/A		
Cooking Fuel Mix	Diverse Modern Fuels	China	**Data Completeness**	N/A - sensitivity analysis	N/A	Future cooking fuel mixes are included as part of the sensitivity analysis. See SI3 or additional detail and documentation of	SI3
			Temporal Correlation	N/A - sensitivity analysis	N/A		
			Geographic Correlation	N/A - sensitivity analysis	N/A		

Table C-1. Cooking Fuel Mix Data Quality Documentation

Data Type	Fuel Mix Name	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Technological Correlation	Data from technology, process, or materials being studied	N/A	sources and assumptions	
Cooking Fuel Mix	Current	Kenya	**Data Source Reliability**	2009 Kenya Population and Housing Census; data verified based on measurements	High		SI3
			Data Completeness	National Survey; representative data from a sufficient sample of sites over an adequate period, with records for all necessary inputs/outputs	High		
			Temporal Correlation	2009; less than 6 years of difference	Medium High		
			Geographic Correlation	Kenya	High		
			Technological Correlation	Data from technology, process, or materials being studied	High		
Cooking Fuel Mix	BAU 2030	Kenya	**Data Source Reliability**	ERG; qualified estimate; see SI for assumptions.	Medium Low		SI3
			Data Completeness	Representative data from a sufficient sample of sites over an adequate period of time, with records for all necessary inputs/outputs	High		
			Temporal Correlation		N/A		
			Geographic Correlation	Kenya	High		
			Technological Correlation	Data from technology, process, or materials being studied	High		
Cooking Fuel Mix	Ghana Transition (for Kenya)	Kenya	**Data Source Reliability**	ERG adaptation of GLSS2 1993, GLSS3 1995, GLSS4 2000, GLSS5 2008, GLSS6 2014	N/A	Future cooking fuel mixes are included as part of the sensitivity analysis. See SI3 or additional detail and documentation of sources and assumptions	SI3
			Data Completeness	N/A - sensitivity analysis	N/A		
			Temporal Correlation	N/A - sensitivity analysis	N/A		
			Geographic Correlation	N/A - sensitivity analysis	N/A		
			Technological Correlation	Data from technology, process, or materials being studied	N/A		

Table C-1. Cooking Fuel Mix Data Quality Documentation

Data Type	Fuel Mix Name	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
Cooking Fuel Mix	Slow Transition	Kenya	**Data Source Reliability**	ERG adaptation of GLSS2 1993, GLSS3 1995, GLSS4 2000, GLSS5 2008, GLSS6 2014	N/A	Future cooking fuel mixes are included as part of the sensitivity analysis. See SI3 or additional detail and documentation of sources and assumptions	SI3
			Data Completeness	N/A - sensitivity analysis	N/A		
			Temporal Correlation	N/A - sensitivity analysis	N/A		
			Geographic Correlation	N/A - sensitivity analysis	N/A		
			Technological Correlation	Data from technology, process, or materials being studied	N/A		
Cooking Fuel Mix	Diverse Modern Fuels	Kenya	**Data Source Reliability**	Unqualified estimate based on previous LCA results	N/A	Future cooking fuel mixes are included as part of the sensitivity analysis. See SI3 or additional detail and documentation of sources and assumptions	SI3
			Data Completeness	N/A - sensitivity analysis	N/A		
			Temporal Correlation	N/A - sensitivity analysis	N/A		
			Geographic Correlation	N/A - sensitivity analysis	N/A		
			Technological Correlation	Data from technology, process, or materials being studied	N/A		
Cooking Fuel Mix	Current	Ghana	**Data Source Reliability**	Ghana Living Standards Survey; data verified based on measurements	High		SI3
			Data Completeness	National survey; representative data from a sufficient sample of sites over an adequate period, with records for all necessary inputs/outputs	High		
			Temporal Correlation	2012	High		
			Geographic Correlation	Ghana	High		
			Technological Correlation	Data from technology, process, or materials being studied	High		
Cooking Fuel Mix	BAU 2030	Ghana	**Data Source Reliability**	ERG; qualified estimate; see SI for assumptions.	Medium Low		SI3

Table C-1. Cooking Fuel Mix Data Quality Documentation

Data Type	Fuel Mix Name	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Data Completeness	Representative data from a sufficient sample of sites over an adequate period of time, with records for all necessary inputs/outputs	High		
			Temporal Correlation		N/A		
			Geographic Correlation	Ghana	High		
			Technological Correlation	Data from technology, process, or materials being studied	High		
Cooking Fuel Mix	Moderated Growth	Ghana	**Data Source Reliability**	ERG scenarios project forward based on historic trends in fuel mix development using the provided rationale	N/A	Future cooking fuel mixes are included as part of the sensitivity analysis. See SI3 or additional detail and documentation of sources and assumptions	SI3
			Data Completeness	N/A - sensitivity analysis	N/A		
			Temporal Correlation	N/A - sensitivity analysis	N/A		
			Geographic Correlation	N/A - sensitivity analysis	N/A		
			Technological Correlation	Data from technology, process, or materials being studied	N/A		
Cooking Fuel Mix	Fast Growth	Ghana	**Data Source Reliability**	ERG scenarios project forward based on historic trends in fuel mix development using the provided rationale	N/A	Future cooking fuel mixes are included as part of the sensitivity analysis. See SI3 or additional detail and documentation of sources and assumptions	SI3
			Data Completeness	N/A - sensitivity analysis	N/A		
			Temporal Correlation	N/A - sensitivity analysis	N/A		
			Geographic Correlation	N/A - sensitivity analysis	N/A		
			Technological Correlation	Data from technology, process, or materials being studied	N/A		
Cooking Fuel Mix	Diverse Modern Fuels	Ghana	**Data Source Reliability**	Unqualified estimate based on previous LCA results	N/A	Future cooking fuel mixes are included as part of the sensitivity	SI3
			Data Completeness	N/A - sensitivity analysis	N/A		

Table C-1. Cooking Fuel Mix Data Quality Documentation

Data Type	Fuel Mix Name	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Temporal Correlation	N/A - sensitivity analysis	N/A	analysis. See SI3 or additional detail and documentation of sources and assumptions	
			Geographic Correlation	N/A - sensitivity analysis	N/A		
			Technological Correlation	Data from technology, process, or materials being studied	N/A		

Table C-2. Stove Group LCI Data Quality Documentation

Data Type	Stove Grouping	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
Stove Group LCI	Dung Cake, Traditional	India	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 11 stoves	High		
			Temporal Correlation	1999-2014	N/A		
			Geographic Correlation	India	High		
			Technological Correlation	All emission profiles represent appropriate technology and fuel	High		
Stove Group LCI	Crop Residue, Traditional	Global	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	Used as proxy stove use data for Ghana in the absence of country specific data. Crop residue use is low in Africa, generally.	SI2
			Data Completeness	Represents emissions results of 26 stoves	High		
			Temporal Correlation	1999-2014	N/A		
			Geographic Correlation	India, China	Medium Low		
			Technological Correlation	All emission profiles represent appropriate technology and fuel	High		
Stove Group LCI	Dung Cake, Improved	India	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 4 stoves	Medium		
			Temporal Correlation	1999-2000	N/A		
			Geographic Correlation	India	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. NOx, SOx, ash, PM>2.5<10 and NMVOCs based on traditional, dung stove (IN)	Medium High		
Stove Group LCI	Firewood, three-stone	Global	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 11 stoves	High		
			Temporal Correlation	2012-2015	N/A		

Table C-2. Stove Group LCI Data Quality Documentation

Data Type	Stove Grouping	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Geographic Correlation	Global (no region specified)	Medium Low		
			Technological Correlation	Records for four or five pollutants available for appropriate stove fuel-technology combination. N2O emissions based on three-stone fire (IN). SO2 and NMVOC emissions based on firewood, traditional (IN) scaled to thermal efficiency. NOx based on firewood, trad, GLO	Medium		
Stove Group LCI	Charcoal, Improved	Ghana	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 11 stoves	High		
			Temporal Correlation	2012	N/A		
			Geographic Correlation	Ghana	High		
			Technological Correlation	Records for four or five pollutants available for appropriate stove fuel-technology combination. SO2, NOx, N2O, PM>2.5<10, and NMVOC based on charcoal, improved (IN)	Medium		
Stove Group LCI	Crop Residue, Traditional	China	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 12 stoves	High		
			Temporal Correlation	1999-2010	N/A		
			Geographic Correlation	China	High		
			Technological Correlation	Records for three or less pollutants available for appropriate stove fuel-technology combination. Values for PM>2.5<10, SO2, NOx, N2O, ash, CH4, NMVOC from traditional stoves in India	Medium Low		
Stove Group LCI	Crop Residue, Traditional	India	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 14 stoves	High		
			Temporal Correlation	1999-2014	N/A		
			Geographic Correlation	India	High		

Table C-2. Stove Group LCI Data Quality Documentation

Data Type	Stove Grouping	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Technological Correlation	All emission profiles represent appropriate technology and fuel	High		
Stove Group LCI	Crop Residue, Improved	India	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 8 stoves	Medium High		
			Temporal Correlation	1999-2000	N/A		
			Geographic Correlation	India	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. values for ash, SO2, and NOx from improved stove emissions data for China. Proxy value for PM>2.5<10 from traditional stoves IN, adjusted for thermal efficiency	Medium High		
Stove Group LCI	Crop Residue, Improved	China	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 26 stoves	High		
			Temporal Correlation	1999-2014	N/A		
			Geographic Correlation	China	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. N2O from Crop Residue, Imp, IN	Medium High		
Stove Group LCI	Firewood, three-stone	India	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 4 stoves	Medium		
			Temporal Correlation	1999-2000	N/A		
			Geographic Correlation	India	High		
			Technological Correlation	Records for four or five pollutants available for appropriate stove fuel-technology combination. Proxy emissions for NOx, SO2, and NMVOC from firewood; trad stove -IN, adjusted for thermal	Medium		

Table C-2. Stove Group LCI Data Quality Documentation

Data Type	Stove Grouping	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
				efficiency. Ash value estimated on a typical ash content of wood. (3%). PM<2.5 from Global three-stone emission tests, adjusted for thermal efficiency			
Stove Group LCI	Firewood, Traditional	India	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 14 stoves	High		
			Temporal Correlation	1999-2014	N/A		
			Geographic Correlation	India	High		
			Technological Correlation	All emission profiles represent appropriate technology and fuel	High		
Stove Group LCI	Firewood, Traditional	Global	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 16 stoves	High		
			Temporal Correlation	2002	N/A		
			Geographic Correlation	Global (no region specified)	Medium Low		
			Technological Correlation	Records for four or five pollutants available for appropriate stove fuel-technology combination	Medium		
Stove Group LCI	Firewood, Traditional	China	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 21 stoves	High		
			Temporal Correlation	1999-2012	N/A		
			Geographic Correlation	China	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. Emissions values for traditional stove use in India used for SO2, N2O, PM>2.5<10, adjusted for thermal efficiency. Ash adjusted for thermal efficiency (544 kg of firewood required for 1 GJ of heat in this UP, 371 kg for the ash proxy unit process)	Medium High		

Table C-2. Stove Group LCI Data Quality Documentation

Data Type	Stove Grouping	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
Stove Group LCI	Firewood, Improved	India	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 16 stoves	High		
			Temporal Correlation	1999-2002	N/A		
			Geographic Correlation	India	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. values for ash, SO2, and NMVOCs from improved stove emissions data for China, adjusted for thermal efficiency. Proxy for PM>2.5<10 from trad stove IN, adjusted for thermal efficiency. PM<2.5 is assumed equivalent to emissions reported as Total Suspended Particles	Medium High		
Stove Group LCI	Firewood, Improved	China	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 35 stoves	High		
			Temporal Correlation	1999-2012	N/A		
			Geographic Correlation	China	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. value for N2O from improved stove emissions data for India. Proxy for PM>2.5<10 from trad stove IN, adjusted for thermal efficiency.	Medium High		
Stove Group LCI	Firewood, Improved	Global	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 28 stoves	High		
			Temporal Correlation	2002-2012	N/A		
			Geographic Correlation	Global (no region specified)	Medium Low		
			Technological Correlation	Records for four or five pollutants available for appropriate stove fuel-technology combination.	Medium		

Table C-2. Stove Group LCI Data Quality Documentation

Data Type	Stove Grouping	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
				values for ash, SO2, and NMVOCs from improved stove emissions data for China. Value for N2O from improved stove use in India. All adjusted for thermal efficiency. Proxy for PM>2.5<10 from trad stove IN, adjusted for thermal efficiency.			
Stove Group LCI	Charcoal, Traditional	Global	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 5 stoves	Medium High		
			Temporal Correlation	2002-2015	N/A		
			Geographic Correlation	Global (no region specified)	Medium Low		
			Technological Correlation	Records for four or five pollutants available for appropriate stove fuel-technology combination. Emissions values for traditional charcoal stove in India used for SO2, N2O, PM>2.5<10, and NMVOC, adjusted for thermal efficiency. Ash waste from traditional charcoal stoves in India used as proxy for Ash value, adjusted for stove thermal efficiency. Proxy value for PM<2.5 taken from Charcoal; Impr; GH, adjusted for thermal efficiency	Medium		
Stove Group LCI	Charcoal, Traditional	India	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	This stove has a very high thermal efficiency compared to other traditional stoves.	SI2
			Data Completeness	Represents emissions results of 2 stoves	Medium Low		
			Temporal Correlation	1999-2014	N/A		
			Geographic Correlation	India	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. Emissions values for improved charcoal stove use in GH used for PM<2.5, adjusted for thermal efficiency	Medium High		
Stove Group LCI	Charcoal, Improved	Ghana	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 2 stoves	Medium Low		

Table C-2. Stove Group LCI Data Quality Documentation

Data Type	Stove Grouping	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Temporal Correlation	2012	N/A		
			Geographic Correlation	Ghana	High		
			Technological Correlation	Records for four or five pollutants available for appropriate stove fuel-technology combination. Emissions values for improved charcoal use in India used for SO2, NOx, N2O, PM>2.5<10, and NMVOC, adjusted for thermal efficiency. Ash waste from traditional charcoal stoves in India used as proxy for Ash value, adjusted for thermal efficiency	Medium		
Stove Group LCI	Charcoal, Improved	Kenya	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 4 stoves	Medium		
			Temporal Correlation	2012	N/A		
			Geographic Correlation	Kenya	High		
			Technological Correlation	Records for four or five pollutants available for appropriate stove fuel-technology combination. Emissions values for improved charcoal use in India used for SO2, NOx, N2O, PM>2.5<10, and NMVOC, adjusted for thermal efficiency. Ash waste from traditional charcoal stoves in India used as proxy for Ash value, adjusted for thermal efficiency	Medium		
Stove Group LCI	Coal Powder, Traditional	China	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	All VOCs speciated	SI2
			Data Completeness	Represents emissions results of 5 stoves	Medium High		
			Temporal Correlation	1999-2000	N/A		
			Geographic Correlation	China	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. N2O and PM>2.5<10 from Traditional Coal stoves in IN, adjusted for thermal efficiency	Medium High		

Table C-2. Stove Group LCI Data Quality Documentation

Data Type	Stove Grouping	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
Stove Group LCI	Coal Powder, Improved	China	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	All VOCs speciated	SI2
			Data Completeness	Represents emissions results of 3 stoves	Medium		
			Temporal Correlation	1999-2000	N/A		
			Geographic Correlation	China	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. Proxy values for N2O and PM>2.5<10 taken from Heat from Coal; from Improved Stoves - IN, adjusted for thermal efficiency	Medium High		
Stove Group LCI	Coal, Angethi	India	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 1 stoves	Low		
			Temporal Correlation	2014	N/A		
			Geographic Correlation	India	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. Proxy value from PM<2.5 from coal powder, improved, CN, adjusted for thermal efficiency	Medium High		
Stove Group LCI	Coal Briquette, Improved	China	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	Missing N2O emissions	SI2
			Data Completeness	Represents emissions results of 4 stoves	Medium		
			Temporal Correlation	1999-2000	N/A		
			Geographic Correlation	China	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. Proxy PM>2.5<10value from honeycomb coal minus PM<2.5, adjusted for thermal efficiency	Medium High		
Stove Group LCI		China	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	All VOCs speciated	SI2

Table C-2. Stove Group LCI Data Quality Documentation

Data Type	Stove Grouping	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
	Honeycomb Coal, Traditional		**Data Completeness**	Represents emissions results of 8 stoves	Medium High		
			Temporal Correlation	1999-2010	N/A		
			Geographic Correlation	China	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. PM <2.5 approximated by measured quantity of total suspended particles. Proxy value for N2O from Heat from Coal Trad - IN, adjusted for thermal efficiency difference Proxy value for PM>2.5<10 from Heat from Honeycomb Coal; Improved - CN, adjusted for thermal efficiency difference	Medium High		
Stove Group LCI	Honeycomb Coal, Improved	China	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 13 stoves	High		
			Temporal Correlation	1999-2008	N/A		
			Geographic Correlation	China	High		
			Technological Correlation	All emission profiles represent appropriate technology and fuel	High		
Stove Group LCI	Coal Gas	China	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 2 stoves	Medium Low		
			Temporal Correlation	1999-2000	N/A		
			Geographic Correlation	China	High		
			Technological Correlation	All emission profiles represent appropriate technology and fuel	High		
Stove Group LCI	Kerosene, Wick	India	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	Missing PM>2.5<10	SI2
			Data Completeness	Represents emissions results of 2 stoves	Medium Low		

Table C-2. Stove Group LCI Data Quality Documentation

Data Type	Stove Grouping	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Temporal Correlation	1999-2000	N/A		
			Geographic Correlation	India	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. Emissions values for kerosene stove use in China used for SO2, NMVOCs and NOx, adjusted for thermal efficiency. Missing PM>2.5<10. Emission factor for Total Suspended Particles considered to be PM<2.5	Medium High		
Stove Group LCI	Kerosene, Pressure	India	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	Missing PM>2.5<10	SI2
			Data Completeness	Represents emissions results of 2 stoves	Medium Low		
			Temporal Correlation	1999-2000	N/A		
			Geographic Correlation	India	High		
			Technological Correlation	Records for four or five pollutants available for appropriate stove fuel-technology combination. Emissions values for kerosene stove use in China used for SO2, NMVOCs and NOx. Emission factor for Total Suspended Particles considered to be PM<2.5	Medium		
Stove Group LCI	Kerosene	China	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	Missing PM>2.5<10	SI2
			Data Completeness	Represents emissions results of 4 stoves	Medium		
			Temporal Correlation	1999-2000	N/A		
			Geographic Correlation	China	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. Emissions values for kerosene stove use in India used for N2O	Medium High		
Stove Group LCI	Kerosene	Global	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	Missing PM>2.5<10	SI2

Table C-2. Stove Group LCI Data Quality Documentation

Data Type	Stove Grouping	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Data Completeness	Represents emissions results of 8 stoves	Medium High		
			Temporal Correlation	1999-2000	N/A		
			Geographic Correlation	Global (no region specified)	Medium Low		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination	Medium High		
Stove Group LCI	LPG	India	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	Missing PM>2.5<10	SI2
			Data Completeness	Represents emissions results of 2 stoves	Medium Low		
			Temporal Correlation	1999-2000	N/A		
			Geographic Correlation	India	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. Emissions values for LPG stove use in China used for NOx, SO2, and NMVOCs. Emission factor for Total Suspended Particles considered to be PM<2.5	Medium High		
Stove Group LCI	LPG	Global	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	Missing PM>2.5<10, All VOCs speciated	SI2
			Data Completeness	Represents emissions results of 6 stoves	Medium High		
			Temporal Correlation	1999-2000	N/A		
			Geographic Correlation	Global (no region specified)	Medium Low		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination	Medium High		
Stove Group LCI	LPG	China	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	Missing PM>2.5<10, All VOCs speciated	SI2
			Data Completeness	Represents emissions results of 4 stoves	Medium		
			Temporal Correlation	1999-2000	N/A		

Table C-2. Stove Group LCI Data Quality Documentation

Data Type	Stove Grouping	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Geographic Correlation	China	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. Emissions values for kerosene stove use in India used for N2O	Medium High		
Stove Group LCI	Natural Gas	China	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	Missing PM>2.5<10	SI2
			Data Completeness	Represents emissions results of 3 stoves	Medium		
			Temporal Correlation	1999-2000	N/A	Use phase emissions used also for India.	
			Geographic Correlation	China	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. Proxy value for SO2 from LPG China, adjusted for thermal efficiency. Proxy value for N2O from LPG India, adjusted for thermal efficiency	Medium High		
Stove Group LCI	Ethanol	India	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	Missing values for NOx, PM>2.5<10, N2O, NMVOC.	SI2
			Data Completeness	Represents emissions results of 4 stoves	Medium		
			Temporal Correlation	2009	N/A	SO2 not applicable due to negligible S content.	
			Geographic Correlation	India	High		
			Technological Correlation	All emission profiles represent appropriate technology and fuel. Only emissions of CO, CH4, PM2.5, and CO2 available in laboratory testing results	Low		
Stove Group LCI	Biogas	India	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 3 stoves	Medium		
			Temporal Correlation	1999-2014	N/A		

Table C-2. Stove Group LCI Data Quality Documentation

Data Type	Stove Grouping	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Geographic Correlation	India	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. Proxy for PM<2.5 from Biogas - RAF	Medium High		
Stove Group LCI	Biogas	Africa	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High		SI2
			Data Completeness	Represents emissions results of 1 stoves	Low		
			Temporal Correlation	2011	N/A		
			Geographic Correlation	Ghana	High		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. Missing Values for N2O, CH4, and PM>2.5<10 taken from 'Biogas, Modern, IN'	Medium High		
Stove Group LCI	Biomass Pellets (wood), Gasifier Stove	Global	**Data Source Reliability**	Verified measurements from peer reviewed academic literature	High	Most data from China	SI2
			Data Completeness	Represents emissions results of 5 stoves	Medium High		
			Temporal Correlation	2012-2014	N/A		
			Geographic Correlation	Global (no region specified)	Medium Low		
			Technological Correlation	Records for six or more pollutants available for appropriate stove fuel-technology combination. NOx from firewood, improved GLO adjusted for thermal efficiency. SO2 from firewood, improved CN adjusted for thermal efficiency. N2O, NMVOCs from firewood, improved IN adjusted for thermal efficiency	Medium High		

Table C-3. Electricity Mix Data Quality Documentation

Data Type	Scenario Name	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
Electricity Mix	Current Mix	India, China, Kenya, Ghana	**Data Source Reliability**	IEA data (IEA 2013a-d); Data verified based on measurements	High	Generation technology is not specified. Regionally specific or regionally adapted unit processes from ecoinvent used to represent combustion technology	SI4
			Data Completeness	Representative data from a sufficient sample of sites over an adequate period, with records for all necessary inputs/outputs	High		
			Temporal Correlation	2013	High		
			Geographic Correlation	Specific to each country	High		
			Technological Correlation	Data from a different technology using the same process and/or materials	Medium High		
Electricity Mix	Future Mix - TERI BAU, Hybrid, Efficiency	India	**Data Source Reliability**	The Energy and Resources Institute, India (TERI 2006); Economic modeling approach; Data verified based on some assumptions and/or standard science and engineering calculations	Medium High	Generation technology is specified. LCI of regionally specific or regionally adapted unit processes from ecoinvent were adjusted to reflect the efficiency and emissions of reported combustion technologies	SI4
			Data Completeness	N/A	N/A		
			Temporal Correlation	2021 and 2031	High		
			Geographic Correlation	India	High		
			Technological Correlation	Specifies combustion technology; Data from technology, process, or materials being studied	High		
Electricity Mix	IEA 2050, IEA Blue Map	India	**Data Source Reliability**	IEA Report (IEA 2010); Data verified based on some assumptions and/or standard science and engineering calculations	Medium High	Generation technology is specified. LCI of regionally specific or regionally adapted unit processes from ecoinvent were adjusted to reflect the efficiency and emissions of reported combustion technologies	SI4
			Data Completeness	N/A	N/A		
			Temporal Correlation	2050	High		
			Geographic Correlation	India	High		

Table C-3. Electricity Mix Data Quality Documentation

Data Type	Scenario Name	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Technological Correlation	Specifies combustion technology; Data from technology, process, or materials being studied	High		
Electricity Mix	Low Carbon 2050	India	**Data Source Reliability**	Gambhir et al. 2012; Economic modeling approach; data verified based on some assumptions and/or standard science and engineering calculations	Medium High	Description of modeling method from Gambhir et al. 2012: "an integrated assessment model combining the energy-technology TIMES model with a climate module to integrate economic activity with energy usage"	SI4
			Data Completeness	N/A	N/A		
			Temporal Correlation	2050	High		
			Geographic Correlation	India	High		
			Technological Correlation	Data from a different technology using the same process and/or materials	Medium High		
Electricity Mix	EIA 2030	India	**Data Source Reliability**	EIA Report; Data verified based on some assumptions and/or standard science and engineering calculations	Medium High	Generation technology is not specified. Regionally specific or regionally adapted unit processes from ecoinvent used to represent combustion technology	SI4
			Data Completeness	N/A	N/A		
			Temporal Correlation	2030	High		
			Geographic Correlation	India	High		
			Technological Correlation	Generation technology is not specified; Data from a different technology using the same process and/or materials	Medium High		
Electricity Mix	BCG Slow Shift - 2030, BCG Base - 2030, BCG Clean - 2030	China	**Data Source Reliability**	Michael et al. 2013; Data verified with many assumptions, or non-verified but from quality source	Medium	Generation technology is not specified. Regionally specific or regionally adapted unit processes from ecoinvent used to represent combustion technology	SI4
			Data Completeness	N/A	N/A		
			Temporal Correlation	2030	High		
			Geographic Correlation	China	High		

Table C-3. Electricity Mix Data Quality Documentation

Data Type	Scenario Name	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Technological Correlation	Generation technology is not specified; Data from a different technology using the same process and/or materials	Medium High		
Electricity Mix	LBNL Scenarios	China	**Data Source Reliability**	Zhou et al. 2011; economic modeling considering technology specific factors such as saturation, efficiency, or usage; data verified based on some assumptions and/or standard science and engineering calculations	Medium High	Generation technology is specified. LCI of regionally specific or regionally adapted unit processes from ecoinvent were adjusted to reflect the efficiency and emissions of reported combustion technologies	SI4
			Data Completeness	N/A	N/A		
			Temporal Correlation	2030-2050	High		
			Geographic Correlation	China	High		
			Technological Correlation	Specifies combustion technology; Data from technology, process, or materials being studied	High		
Electricity Mix	IEA 2050 Baseline, IEA Blue Map	China	**Data Source Reliability**	IEA Report; Data verified based on some assumptions and/or standard science and engineering calculations	Medium High	Generation technology is specified. LCI of regionally specific or regionally adapted unit processes from ecoinvent were adjusted to reflect the efficiency and emissions of reported combustion technologies	SI4
			Data Completeness	N/A	N/A		
			Temporal Correlation	2050	High		
			Geographic Correlation	China	High		
			Technological Correlation	Specifies combustion technology; data from technology, process, or materials being studied	High		
Electricity Mix	Republic of Kenya 2031 Grid Scenarios	Kenya	**Data Source Reliability**	ROK 2011; study uses least cost method of technology selection; data verified based on some assumptions and/or standard science and engineering calculations	Medium High	Generation technology is not specified. Regionally specific or regionally adapted unit processes from ecoinvent used to	SI4
			Data Completeness	N/A	N/A		
			Temporal Correlation	2011-2031	High		

Table C-3. Electricity Mix Data Quality Documentation

Data Type	Scenario Name	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Geographic Correlation	Kenya	High	represent combustion technology	
			Technological Correlation	Generation technology is not specified; data from a different technology using the same process and/or materials	Medium High		
Electricity Mix	McKinsey 2040	Kenya	**Data Source Reliability**	Castellano et al. 2015; demand driven estimates of future energy demand; data verified based on some assumptions and/or standard science and engineering calculations	Medium High	Use empirical data based on GDP growth from approximately 20 countries	SI4
			Data Completeness	N/A	N/A		
			Temporal Correlation	2040	High		
			Geographic Correlation	West Africa	Medium Low		
			Technological Correlation	Generation technology is not specified; data from a different technology using the same process and/or materials	Medium High		
Electricity Mix	Low Carbon	Kenya	**Data Source Reliability**	Unqualified estimate based on previous LCA results	Low	Generation technology is not specified. Regionally specific or regionally adapted unit processes from ecoinvent used to represent combustion technology	SI4
			Data Completeness	N/A	N/A		
			Temporal Correlation	Not associated with a specific time period	N/A		
			Geographic Correlation	Kenya; relies on renewable resources that other references indicate are available in Kenya	High		
			Technological Correlation	Generation technology is not specified; data from a different technology using the same process and/or materials	Medium High		
Electricity Mix	Ghana EC Scenarios	Ghana	**Data Source Reliability**	GEC 2006; National Energy Plan; data verified with many assumptions, or non-verified but from quality source	Medium	Generation technology is not specified. Regionally specific or regionally adapted unit processes from ecoinvent used to	SI4
			Data Completeness	N/A	N/A		
			Temporal Correlation	2020	High		

Table C-3. Electricity Mix Data Quality Documentation

Data Type	Scenario Name	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
			Geographic Correlation	Ghana	High	represent combustion technology	
			Technological Correlation	Generation technology is not specified; data from a different technology using the same process and/or materials	Medium High		
Electricity Mix	Low Carbon	Ghana	**Data Source Reliability**	Qualified estimates based on 2030 renewable energy capacity estimates from IRENA 2013	Medium Low	Generation technology is not specified. Regionally specific or regionally adapted unit processes from ecoinvent used to represent combustion technology	SI4
			Data Completeness	N/A	N/A		
			Temporal Correlation	Not associated with a specific time period	N/A		
			Geographic Correlation	Ghana	High		
			Technological Correlation	Generation technology is not specified; data from a different technology using the same process and/or materials	Medium High		
Electricity Mix	Low Carbon	Ghana	**Data Source Reliability**	Unqualified estimate based on previous LCA results	Low	Generation technology is not specified. Regionally specific or regionally adapted unit processes from ecoinvent used to represent combustion technology	SI4
			Data Completeness	N/A	N/A		
			Temporal Correlation	Not associated with a specific time period	N/A		
			Geographic Correlation	Ghana; relies on energy resources that other references indicate are available in Kenya	High		
			Technological Correlation	Generation technology is not specified; data from a different technology using the same process and/or materials	Medium High		

Table C-4. LCI Unit Process Data Quality Documentation

Data Type	Unit Process Name	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
LCI Unit Process Data	Current, Average Kiln	Ghana	**Data Source Reliability**	Peer reviewed literature; verified measurements	High	A single quantity estimate is available for each flow value	SI6
			Data Completeness	LCI data based on two publications. Missing estimate of SO2 emissions	Medium		
			Temporal Correlation	Main emissions data published in 2011, remainder from 2003	Medium, Medium Low		
			Geographic Correlation	Ghana, Africa	High		
			Technological Correlation	Earthen mound kiln	High		
LCI Unit Process Data	Crop Residue	India, China, Ghana	**Data Source Reliability**	Data verified with many assumptions, or non-verified but from quality source	Medium	Please see SI5 for specifics regarding data sources, assumptions and aggregation	SI5
			Data Completeness	Smaller number of sites and shorter periods or incomplete data from an adequate number of sites or periods	Medium Low		
			Temporal Correlation	Less than 15 years of difference	Medium Low		
			Geographic Correlation	Input values specific to nation of interest when possible; Emission values calculated on the basis on nation specific inputs; average data from larger area or specific data from a close area	Medium High		
			Technological Correlation	Not specific agricultural production method represented. Intended to cover a wide range of production practices	N/A		

Table C-4. LCI Unit Process Data Quality Documentation

Data Type	Unit Process Name	Country	Data Quality Criteria	Qualitative Data Quality Discussion	Quality Estimate	Additional Note on Quality	SI File
LCI Unit Process Data	Biogas & Bioslurry Land Application	Global	**Data Source Reliability**	LCI values based on: peer reviewed literature; verified measurements or data verified based on some assumptions and/or standard science and engineering calculations	Medium High	Please see SI7 for specifics regarding data sources, assumptions and aggregation	SI7
			Data Completeness	Most flow values based on the average of 3 or more literature sources with the full range of reported values being reflected in the uncertainty analysis; smaller number of sites, but an adequate period of time	Medium High		
			Temporal Correlation	For the given biogas production and application methods LCI inputs/outputs are not expected to be time sensitive	N/A		
			Geographic Correlation	Global (no region specified)	Medium Low		
			Technological Correlation	All emission profiles represent appropriate material	High		

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