Life-Cycle Assessment of Stacked Cooking Fuels in Rural India

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Submitted by: John Dees, Jack Chang, Matthew Mayes, Yue (Nicole) Wu, and Surabhi Yadav

Instructor: Professor Arpad Horvath

Abstract

In 2016, in an effort to reduce the national environmental health burden, the government of India launched a policy effort, *Pradhan Mantri Ujjwala Yojana* (PMUY), with the goal of subsidizing 80 million new liquefied petroleum gas (LPG) cookstove connections by 2019. As of 2017, an earlier goal of 50 million connections had been met, and the government extended its LPG goal for 2019. Recently the issue has been raised that the complete adoption of LPG and the replacement of traditional biofuels hasn't occurred as hoped. Rather, due the perceived high price of LPG and difficulty obtaining refills, varying degrees of fuel stacking with traditional and modern fuels are common. While previous studies have performed life-cycle impact assessments to compare LPG and traditional fuels, none have taken into account fuel stacking and rebound effects. This study seeks to quantify the health and climate relevant impacts of various fuel stacking scenarios both at the household and policy-wide scales. We expect the analysis to illuminate a more realistic relationship between the costs of implementing such an ambitious policy and realized benefits at this stage of India's energy transition.

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Executive Summary

Every day, 2.8 billion people across the globe depend on solid fuel (e.g. biomass and coal) burned in smoky, inefficient stoves to cook their meals. Twenty-five percent of these solid fuel users live in India. The health impacts are well understood: Smoke from household cooking is the second leading risk factor for disease in the developing world and is responsible for about 4.3 million premature deaths annually, disproportionately affecting women and children. In an unprecedented effort, the government of India distributed 50 million new liquefied petroleum gas (LPG) stoves and fuel canisters to poor households with a unique broad-scale crowdfunding campaign and a US$1.5 billion budget. This program is known as *Pradhan Mantri Ujjwala Yojana* (PMUY).

The intended application of this LCIA analysis is to assess the potential health and environmental impacts of the PMUY policy given the dual problems of rebound and fuel stacking in households. Additionally, this study seeks to understand the implications of a new policy mandating that LPG be manufactured with 30% methanol from coal. The purpose of this research is to model realistic household cooking fuel use scenarios to quantify the policy's health and environmental implications at both the household and national level. Moreover, we intend to perform sensitivity analyses quantifying the range of outcomes associated with differing assumptions about fugitive emissions and cookstove efficiency. The intended audience of this report would include policy decision-makers and academic researchers concerned with the health and environmental impacts of energy policy in India.

We analyze the "cradle to grave" life cycle of LPG and biomass cooking fuels. OpenLCA software was used to perform LCIA. The methodology follows directives from the International Organization ISO 14040-ISO 14044 series and the procedure entails: 1) Goal and Scope 2) Inventory Analysis 3) Impact Assessment.

The ReCiPe impact assessment methodology was used to determine endpoint environmental impacts. The stages of impact assessment include: 1) Classification 2) Characterization and 3) Normalization. Our model will seek to understand life-cycle impacts of cooking fuel use as it's likely to occur under a set of fuel stacking scenarios at the household level. Using the functional unit of 1 GJ as a basis, we model the impacts of generating 1 GJ of cooking energy with various shares of LPG and biomass (wood and dung cake) fuels as indicated by the literature on fuel stacking and rebound effects. The impacts are measured principally in global warming potential and PM2.5 produced.

1. Introduction

People worldwide have cooked with wood, dung and other biomass for centuries and suffered from illnesses caused by inhaling the resulting emissions (Smith & Pillarisetti 2017). The definitions may not have existed millenia ago, but we now know that regular exposure to particulate matter emanating from cookfires using solid fuels causes a range of respiratory illnesses, cardiovascular disease, pneumonia and lung cancer, among other illnesses (Smith 2000).

Today, about 40 percent of people globally still use wood, coal and agricultural residues as cooking fuels (Smith & Pillarisetti 2017). The International Energy Agency estimated in 2016 that 3.5 million people die prematurely every year due to household air pollution (HAP) largely caused by cooking with biomass, with a million dying annually in India alone (Patnaik et al.2017). Cooking with biomass also generates about a third of the ambient air pollution in India (Chafe et al.2015) - an environmental problem that has reached epidemic proportions in recent decades in India. In South Asia, 200,000 deaths every year were caused by ambient air pollution in 2010, the vast majority of them occurring in India (Chafe *et al.*2015). According to the 2013 Global Burden of Disease Study, household air pollution was ranked as the top environmental health risk factor globally (Smith & Pillarisetti 2017).

At the same time, expanded access to modern fuels and clean sources of energy is becoming more common, reducing respiratory illnesses and other health problems caused by cooking with solid fuels. LPG, which is seen as a much cleaner burning cooking fuel, was first introduced for domestic use in India in the 1950s (Smith 2017)**.** Since then, the Indian government has continued to subsidized the purchase of LPG. Nonetheless, until recently, it has remained affordable only for the middle-class and overwhelmingly urban households in India.

It wasn't until 2014 that the Indian government addressed the lack of access to clean fuels as both a public and environmental health issue. In 2015, the government along with three state-owned oil and gas companies (IOC, BPCL, HPCL) launched programs to help the rural poor access and purchase LPG as a replacement cooking fuel.

Pahal: A direct transfer program that deposits fuel subsidies directly into bank accounts. This was developed partially to help reduce the illicit use of fuel subsidies outside the household cooking fuel sector (Gould et al. 2018).

Giveitup: A program that encourages upper- and middle-class households to voluntarily give up their fuel subsidy, with the funds used to expand LPG access to India's rural poor. More than 10 million Indian households are estimated to have participated in the campaign since its conception (Gould et al 2018).

Pradhan Mantri Ujjwala Yojana (PMUY): PMUY also known as Ujjwala is an ongoing initiative that was built on the success of both Pahal and the *Giveitup* campaigns in expanding LPG access to rural areas (Mittal et al. 2017). The Indian government has aligned PMUY with its voluntary implementation of the UN's Sustainable Development Goals. Ujjwala has a gender-focused approach to dissemination and seeks to empower women who are traditionally responsible for cooking and disproportionately suffer from the effects of indoor household air pollution due to the use of solid cooking fuels.

Launched on May 1, 2016, PMUY set an initial goal of distributing 5 crore (50 million) LPG connections by March 31, 2019. The dissemination strategy moved more quickly than anticipated, and in early August 2018 the initial goal of 50 million LPG connections was met. As of October 18, 2019, PMUY's official website (http://www.pmujjwalayojana.com/) listed the number of disseminated connections as 56,788,976. The success of PMUY has led to revisions for its target goals. By March 2019, the government aims to have installed 80 million new LPG connections with a budget allocation of US $1.7 billion.

Although PMUY is largely motivated by its potential for health and environmental impacts, to date there has been no effort to precisely quantify or characterize the effect that PMUY's LPG dissemination targets would have on current levels of indoor and ambient air pollution in India. The president of the women's wing of India's Biju Janata Dal political party recently criticized PMUY, citing that only 16% of the LPG connections disseminated under the scheme were refilled in 2017-2018 due to a hike in fuel prices (The New India Express 2018). These allegations expose concerns regarding fuel stacking, which muddies the potential impact of improved cooking fuel interventions. Additionally, it was announced in September that the government was drawing up plans to reduce subsidized fuel costs by blending LPG with methanol and scaling up the production of coal produced domestically (The Economic Times 2018). As of yet there exists no quantification of the relative emissions impact of adding methanol to LPG.

2. Problem Statement

In this paper, we aim to bridge the existing gaps in knowledge around LPG distribution in India using LCIA methods.

The existing literature reports extensive evidence for the health and environmental impacts of biofuel-based cook stove use *(chulhas)*. However, these studies have analyzed household level impacts and not the complete life cycle of LPG distribution. This LCIA seeks to address this literature gap by modeling household fuel stacking scenarios and estimating the relevant impacts to human health at the household level.

With the expectation of tremendous health and environmental benefits, the current government policy aims to have installed 80 million new LPG connections by 2019. Despite its ambitious goal, the policy's effectiveness hinges on the adoption and use of subsidized connections in rural households. Previous studies have described a low adoption rate of cleaner fuels due to a lack of affordability, difficulty of access and cultural preferences. Evidence shows that providing access and affordability to clean fuels alone doesn't ensure 100% adoption. This study aims to better clarify the implications of "fuel stacking" and "rebound effects," whereby households adopt modern cooking fuels but then revert to some level of traditional biomass use. Conclusions from this analysis have potential implications for the Indian government's implementation of the LPG policy as well as related impact assessment and resource allocation decisions.

3. Key Questions

- What are the potential household health impacts of LPG under various fuels stacking scenarios?
- What are the tradeoffs between health impacts and environmental impacts regarding cooking fuel policy in India?
- What is the sensitivity of these results given different assumptions for cookstove efficiencies and transport distances for LPG supply chains?

4. Background

4.1 Emissions Performance and Health Relevant Impacts of LPG Cookstoves

As an alternative to burning solid fuels for cooking, LPG use is widely seen as an important solution for mitigating indoor household air pollution. To date, only a handful of studies have broadly assessed the performance efficiency and attributable emissions of different LPG cookstoves (see Table 1**.** Previous studies used questionably representative cookstove units and testing facilities. The bulk of existing literature is also characterized by small samples of tested cookstove units and LPG fuel compositions that limit the general accuracy of emissions estimates. Most recently and a notable exception, Shen et al. (2018) conducted 89 laboratory tests to quantify the efficiency of five commercially available household LPG cookstoves using different fuel compositions (% Butane/Propane by mass). Additionally, the study varied some characteristics thought to affect stove performance (stove burner level, air control and stove deterioration) to broaden the study's sensitivity to different operating conditions.

Results from the study confirmed the improved efficiency and lower emissions of LPG cookstoves relative to solid fuels-based cooking. Approximately 90% of the collected PM2.5 data was below the detectable limit. For the observed data, the maximum recorded PM2.5 emission factor present in the study was **6.7 mg/MJd**, within the Sub-Tier 4 (best rating) for stove performance as outlined by the International Organization for Standardization's guidelines for evaluating cookstove performance (ISO IWA 2012).

As of yet, owing to the lack of emissions performance data for LPG cookstove units, the health relevant impacts of LPG cookstove usage haven't been quantified. Collecting emissions performance data is a necessary precursory step toward developing inventories and evaluating the impacts of LPG interventions on air quality and human health. This paper intends to build on the data from Shen et al. (2018) to characterize the health relevant impacts of the Indian government's planned LPG distribution policy.

Working from Singh et al. (2014), the published estimate for the amount of useful energy needed for cooking per day per household is **11 MJ/day**. The estimated average daily emissions of PM2.5 from an LPG stove unit is **73.7 mg**.

Table 1. Studies Evaluating Efficiency and Emissions From LPG Cookstoves

Study:	Description	Sample Size of LPG Stove Unit Tests (Unit, Fuel)	Tested differences in LPG fuel composition	Analyzed Stove Power Level, burner air control, and stove deterioration	Attributable Health Impact Assessment
(Shen, et al. 2018)	An investigation into efficiencies and air pollutant emission factors from LPG cookstoves under variable conditions	89	Yes	Yes	No
(Zhang, et al. 1999)	An examination of carbonyl emission factors for commonly used cookstoves in China including LPG	3	No	No	No
(Zhang, et al. 2000)	A report on tested fuel/stove combinations and the calculated emissions factors of direct and indirect GHGs and other airborne pollutants in China	3	No	No	No
(Smith, et al. 2000)	EPA report studying the efficiency and pollutant emissions from LPG household use in India	3	No	No	No
(Habib et al. 2008)	An investigation into climate relevant emissions from fuels (including LPG) compared to biomass in India	1	No	No	No
(MacCarty et al 2010)	A study of emissions from the burning of propane in a single - burner mass-produced LPG camping stove	1	No	No	No

(Shen et al. 2017)	A study comparing ultra fine particle emissions from different household cookstove systems	1	No	No	No

4.2 Health Impacts due to Household Air Pollution

Over the last two decades, plenty of evidence has documented adverse health impacts due to indoor and ambient air pollution. The health impacts caused by incomplete combustion of solid fuels (firewood, coal, cow-dung cakes, etc.) in cookstoves are characterized under what is known as “the environmental health pathway.” The pathway starts with sources of emissions, then moves to environmental levels, human exposures, doses within the body and finally to health impacts. According to the 2017 Global Burden of Disease indicators from the Institute of Health Metrics and Evaluation, 2.6 million to 4.3 million deaths globally are caused by household air pollution (HAP) each year. In Southeast Asia, HAP was ranked third among risk factors when assessed in disability-adjusted life years (DALYs) according to all health outcomes and sixth as a contributor to non-communicable diseases.

The main health effects caused by chronic exposure to HAP include acute respiratory infections (ARI), chronic obstructive pulmonary disease (COPD) and lung cancer. Intermediate evidence also indicates extended HAP exposure can cause blindness, tuberculosis, asthma, adverse pregnancy outcomes and heart disease (Smith et al., 2000). The burden of disease is significantly higher for women and children under the age of five with much greater exposure to cookstoves compared to men, especially in poor communities.

That disproportionate disease burden for women and children certainly holds true in rural India. An estimated 1 million premature deaths and 31.4 million DALYs are attributed to solid cooking fuel-derived HAP exposure in the country. HAP accounts for 6% of India’s total national disease burden, placing it among the country’s most significant environmental health risk factors (Desai et al., 2004). About 525,000 deaths can be attributed to Acute Lower Respiratory Infections, and about 350,000 deaths can be attributed to chronic obstructive pulmonary diseases (COPD) in India. Around 16.9 million disability-adjusted life years are lost due to HAP caused by solid fuel use, mostly from lost productivity due to illness. An estimated 140,000 children under age five die annually in India due to HAP-induced illnesses (HEI Household Air Pollution Working Group, 2018). This accounts for ~8% of under-five deaths in India. An estimated 4 percent of deaths of children under age five are caused by HAP-related pneumonia. (Pillarisetti et al., 2017).

4.3 Health Impacts due to Ambient Air Pollution

The health impacts of cooking with biomass are not limited to within the household. An estimated 25 percent of ambient air pollution in India is caused by cookstoves using biomass (Chafe *et al.*2015). One study found that as much as 52 percent of all ambient PM2.5 in the northern Indian state of Haryana came from residential cooking and heating using biomass (Fleming *et al.*2018). Across India, high levels of ambient air pollution are caused by diverse sources such as vehicle and industrial emissions, in addition to the burning of biomass. In more than half of all Indian cities monitored by the National Air Quality Monitoring Programme, ambient levels of PM10 were considered critical, with more than a third of cities' air quality measurements exceeding the levels considered safe (Ministry of Health and Family Welfare 2015). Ending or drastically reducing the practice of burning biomass would make a considerable impact on what India's Ministry of Health and Family Welfare has identified as "the world's largest single environmental risk."

While the use of LPG cookstoves is known to reduce household air pollution relative to biomass-based cooking, the question remains whether LPG is the right substitute for biomass in reducing ambient air pollution. In its life cycle, LPG emits methane during production. Some estimate the leakage at 1 percent of LPG produced (Singh *et al.*2014). Additionally, the transport and distribution of LPG releases butane and propane, components of ozone, expelled mainly when connections or disconnections are made between pipes, stores and cylinders. An estimated .3 percent of LPG is lost due to leakage between production and delivery to the household (Jungbluth 1997). The health impacts of such leakage can vary depending on where the leakage occurs and in what amounts.

Table 2. Studies evaluating ambient air pollution in India caused by biomass burning

Authors, year	Study description	Relevant points
(Fleming et al. 2018)	Study quantifies emissions of CO, CO2 and 76 different VOCs from 55 cook fires carried out by a local cook in a village home cooking typical meals.	Researchers believe 22-52 percent of ambient PM 2.5 in Haryana comes from residential cooking and heating. Residential cooking produces 2.6 Tg of PM 2.5 annually in India.
(Chafe et al. 2015)	Describes the contribution of burning biomass for cooking to ambient air pollution across different regions globally.	50-70 percent of black carbon and 60-90 percent of organic carbon emissions come from residential coal and biomass use in India and China. Globally, 12 percent of ambient PM2.5 come from household use of solid cooking fuels - 26 percent in South Asia. Ninety percent of fine particles from household cooking escape to open air.

		In 2010, ambient air pollution from household burning of coal and biomass was responsible for 200,000 deaths in South Asia.
(Smith and Pillarisetti 2017)	Describes the contribution of burning biomass for cooking to ambient air pollution within India.	Twenty to -25 percent of ambient PM2.5 in India comes primarily from household cooking.
(Ministry of Health and Family Welfare 2015)	An Indian government white paper on the health risks of air pollution.	Studies have shown that emissions from cooking using biomass contributes to around a quarter of ambient PM2.5 air pollution in the country. In the winter months, the mix of pollution sources changes dramatically. The use of biomass, primarily for heating contributes to as much as 30 percent of particulate pollution in winter.

4.4 Environmental Impact of Cooking Fuels in India

Previous research has investigated the environmental impact of cookstoves based on laboratory simulation. However, several studies measuring the performance and impact of biomass-based cookstoves have used conditions present in the field (Roden et al., 2009), especially for India (Pandey et al., 2017).

A U.S. Environmental Protection Agency (EPA) report has identified 10 impact indicators to measure the environmental impacts of different fuels. The indicators include Global Climate Change Potential (GCCP), Cumulative Energy Demand (CED), fossil depletion, water depletion, particulate matter formation potential, photochemical oxidants formation potential, freshwater eutrophication potential, terrestrial Acidification Potential, ozone depletion potential, Black Carbon (BC) and Short-Lived Climate Pollutants (Cashman et al. 2016).

Based on existing literature, the environmental impact of cookstoves is attributed mainly to emissions pollution (both indoor and outdoor) and its potential to affect climate change (Cashman et al. 2016; Jungbluth 1997, Singh, Gundimeda, and Stucki 2014). Inefficient combustion releases toxic pollutants into the air. Carbon dioxide, methane, black carbon and other short-lived climate pollutants (SLCPs) have a broader impact that contributes to the acidification of soil and water, ozone depletion, forest degradation and the loss of biodiversity. The products of incomplete combustion such as carbon monoxide and methane have greater global warming potentials than carbon dioxide alone (Smith et al. 2000).

The scaling of LPG as a replacement for biomass-based cooking presents similar environmental risks. LPG is the product of energy-intensive drilling that can release methane into the atmosphere. LPG is also transported through pipelines that release butane and propane, the latter two of which go on to form ambient ozone.

4.5 Life-Cycle Impact Assessment of Cooking Fuels

An earlier life-cycle impact assessment compared environmental impacts of liquefied petroleum gas (LPG) with kerosene in rural India (Jungbluth, Kollar, and Koβ 1997). The results of the LCA are stratified by assumptions of cookstove efficiency and fuel emissions rates, given the optimal, mean and worst-case efficiencies from the literature at that time for each fuel. Later studies broadened the scope and compared the life-cycle environmental impacts of charcoal, biogas and LPG in Ghana (Afrane and Ntiamoah 2011). Of two recent studies conducted in India, the first compares the life-cycle impacts of 10 fuels: LPG (crude oil), LPG (natural gas), kerosene, coal, electricity, firewood, crop residue, dung cake, charcoal and biogas (Singh, Gundimeda, and Stucki 2014). Unlike previous studies, this paper distinguishes between LPG produced from natural gas and LPG derived from crude oil, and finds that LPG from natural gas has 20 to 30% less environmental impact than that derived from crude oil. Finally, a recent study compiled for the EPA evaluates natural gas, LPG, coal, kerosene, biomass (crop residue, dung, charcoal, firewood, wood pellets), biogas, sugarcane ethanol and dimethyl ether (DME) and analyzes the potential environmental impacts of eight national fuel mix scenarios for both India and China (Cashman et al. 2016).

All of the cited literature show that when comparing the environmental and health impacts of LPG and traditional biofuels, much of the difference emerges from the point of emissions. Most of the health and environmentally relevant emissions of traditional biofuels are emitted at the point of use while LPG fuel is comparably clean at the point of use. However, upstream processes such as production and refinement of LPG do have significant environmental and health impacts that deserve consideration, particularly toxic emissions and global warming potential.

Still, many gaps in the literature need to be addressed. For example, the present literature excludes LPG infrastructure from LCA system boundaries. In one study, the environmental impact of LPG infrastructure is estimated by performing a unit process analysis on petroleum fuels and electricity in the Ecoinvent database - with the results compared to LCA results (Singh, Gundimeda, and Stucki 2014). This environmental impact is often significant and deserves further study in light of the policy-driven expansion of LPG. Another understudied aspect of petroleum-based cooking fuels is fugitive emissions from the production stage. While fugitive methane emissions from coal (Singh, Gundimeda, and Stucki 2014) and anaerobic biogas production (Afrane and Ntiamoah 2011) are modeled in previous studies (at around 1%), the existing literature does not sufficiently explore methane leakage and gas flaring in the production stage of LPG and kerosene. Sensitivity to these leakage assumptions is not well understood.

Additionally, assumptions about stove efficiency significantly influence environmental impact results. Such impacts are markedly higher where biomass-based fuels are concerned and smaller with modern fuels such as LPG (Singh, Gundimeda, and Stucki 2014; Cashman et al. 2016; Jungbluth, Kollar, and Koβ 1997). Additional modeling and sensitivity analysis of these assumptions under varied household fuel mix scenarios would add valuable insight and demarcate uncertainty in LCA results. Finally, existing research has compared differential impacts of cooking fuels at the scales of the functional unit and at the scale of the national energy mix, but no analysis examines the impacts under realistic household adoption scenarios - a key topic that this paper seeks to address.

Table 3. Previous LCA studies of Cooking Fuels

Study:	Description:	Geographic Scope:	Analytical Scope
(Jungbluth, Kollar, and Koβ 1997)	Environmental LCIA comparison of LPG and kerosene cooking fuels	India	Functional unit of 1 GJ. TEMIS 2.0 LCA software Non-standard Impact Categories
{Afrane and Ntiamoah 2011}	Environmental LCIA of charcoal, biogas and LPG cooking fuels	Ghana	Functional Unit of 1 MJ GaBi LCA software CML 2001 Impact Categories
(Singh, Gundimeda, and Stucki 2014)	LCIA of firewood, crop residue, dung cake, charcoal, coal, electricity, LPG, kerosene and biogas cooking fuels	India	Functional Unit of 1 GJ SimaPro 7.3 LCA Software ReCiPe Impact Categories
(Cashman et al. 2016)	EPA report covering extensive cooking fuel mixes. LCIA examines: hard coal, LPG (nat gas), LPG(crude), kerosene, electricity, sugarcane ethanol, biogas (cattle dung), charcoal from wood, biomass pellets, firewood, crop residue, dung cake	India and China	This report examines nine cooking fuel mix scenarios at a national scale and the associated environmental impacts of those ranges of fuel mixes (no fuel share changes by more than 20% of present-day share). OpenLCA Software ReCipE impact Categories

4.6 Fuel Stacking and Rebound Effect

The rebound effect argues that more efficient energy technology incentivizes increased use due to lower cost of generating energy (Berkhout, Muskens, & Velthuijsen 2000). For example, in the case of cooking fuels, a more efficient system might lead to increased consumption of energy for cooking. Given that the monetary cost is much greater for LPG than for biomass, it is unclear how strong if at all the rebound effect might be. However, the possible rebound effect merits consideration here, especially with regard to concurrent use of old cooking technologies alongside new modern cooking fuels.

Fuel stacking occurs when households use different fuels as energy sources at the same time (Cheng and Urpelainen 2014). Specifically during energy transitions, fuel stacking happens as the household uses a cleaner energy source, such as LPG, and then goes back to traditional fuels such as the biomass they used before.

The existing literature identifies fuel stacking as a critical issue in the energy transition process. A recent study identified fuel stacking as a prevailing norm in India as most households continue using firewood even after adopting LPG (Gould and Urpelainen 2018). Another study analyzes fuel stacking for cooking and illumination in India from 1987 to 2010. In that case, fuel stacking was used for cooking since LPG didn't completely replace traditional biomass (the only scenario considered for cooking fuel) (Cheng and Urpelainen 2014).

Currently, limited statistics quantify fuel stacking in India, with disparity among existing estimates. Based on the 2011 National Census, only 11% of rural households use LPG as their primary cooking fuel and the rest rely on burning solid fuels such as firewood, coal and dung for daily cooking and heating (Tripathi et al., 2015). In research covering LPG usage in six Indian states, only 4% of households that own LPG cookstoves use it as their sole source of cooking fuel. Also, less than 60% of those households regard LPG as their primary cooking arrangement (Gould and Urpelainen 2018). However, a comparison study about fuel stacking for cooking indicates approximately 24% of households were exclusively using LPG, and 50.2% of the household fuel expenditure was on wood fuel (Cheng and Urpelainen 2014).

In the context of India's LPG policy, a closer consideration of fuel stacking is necessary to accurately quantify the impact of LPG distribution programs, something this paper looks to address in an expanded LCIA.

5. Modeling Approach and Data

5.1 Goal

The intended application of this LCIA analysis is to assess the potential health and environmental impacts of the PMUY policy given the dual problems of the rebound effect and fuel stacking and enhance policy decision-making in India. The purpose of this research is to model realistic household cooking fuel use scenarios to quantify the policy's health and environmental implications at both the household and national level. Moreover, we intend to add important sensitivity analysis to quantify the range of outcomes associated with differing assumptions about cookstove efficiency. This report's intended audience includes policy-makers and academic researchers concerned with the health and environmental impacts of energy policy in India.

5.2 Scope

The product being compared in this analysis is energy for cooking as provided by LPG and the traditional biomass cooking fuels - wood and dung.

Functional Unit

This study compares the potential environmental and health impacts of cooking fuels in India. The service under comparison is heat for cooking. The functional unit of this analysis is 1 GJ of cooking energy delivered to the cooking pot (estimated annual household cooking energy use is around 2.56 GJ according to Indian government estimates).

System Boundary

We analyze the "cradle to grave" life cycle of LPG and biomass cooking fuels. **Figure 1** illustrates the system boundaries of biomass and LPG cooking fuels commonly used in rural India.

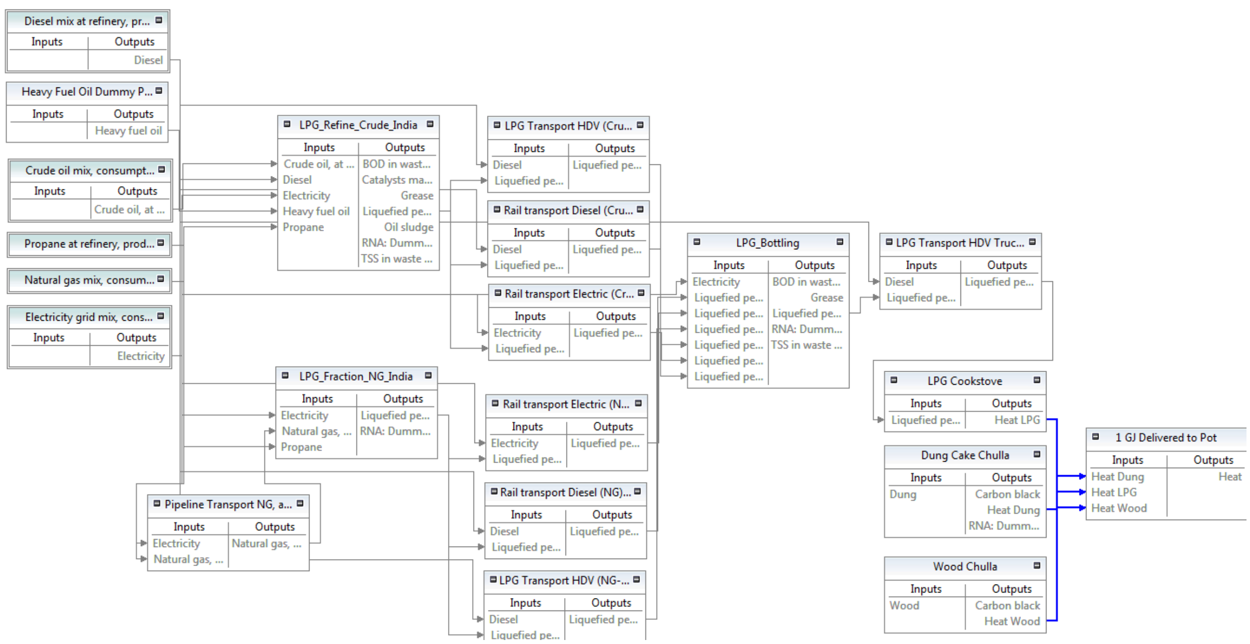

Figure 1. Depicts system boundaries of LCIA analysis for LPG (natural gas), LPG (crude oil), wood and manure/dung cooking fuels. Flow diagram created in OpenLCA.

We have excluded from this study the life-cycle impacts of infrastructure (e.g. roads, refineries, and other capital investments) due to time and resource constraints. Additionally, the manufacturing and end-of-life impacts of cooking stoves have been excluded. Previous literature has found these impacts to be negligible compared with the production and use phases of the fuels (Wilson, Talancon, Winslow, Linares, & Gadgil 2016).

Moreover, unlike LPG, dung and wood have no upstream processes in our model since both are assumed to be collected locally from sources that would already exist regardless of the demand for fuel. While this is not always true, any examination of agricultural practices upstream with regard to biofuels are beyond the scope of this paper.

5.3 LCIA Methodology

Open Life-Cycle Assessment, openLCA, software is used to perform life-cycle impact assessment (LCIA). The methodology follows directives from the International Organization ISO 14040-ISO 14044 series and the procedure entails: 1) Goal and Scope 2) Inventory Analysis 3) Impact Assessment.

The ReCiPe impact assessment methodology is used to determine midpoint environmental impacts and to characterize select life-cycle inventory results. The stages of impact assessment include: 1) Classification 2) Characterization and 3) Normalization. Extraction processes (crude oil and natural gas) and auxiliary energy (electricity, propane, fuel oil, diesel) are modeled using data from GaBi's Ecoinvent 3 standard database and extended database. Core processes (refinement, transportation and use phase) are modeled using values in the cooking fuels literature (Singh, Shen). Both the GaBi and literature data reflect the special case of cooking fuels supply chains in India. We broadly consider 13 ReCiPe environmental impact categories: (1) climate change (GWP100), (2) ozone depletion (OD), (3) human toxicity (HT), (4) photochemical oxidant formation (PCOD), (5) particulate matter (PM) formation, (6) terrestrial acidification (TA), (7) freshwater eutrophication (FWEP), (8) marine eutrophication (MEP), (9) terrestrial ecotoxicity (TET), (10) freshwater ecotoxicity (FWET), (11) marine ecotoxicity (MET), (12) fossil fuel depletion (FD), and (13) metal depletion (MD). These midpoint categories are further aggregated into three endpoint categories (1) human health, (2) ecosystems, and (3) resource surplus cost.

However, our study primarily focuses on the ReCiPe GWP100 and PM categories, and specifically addresses the core emissions of carbon dioxide and PM2.5, as these are the dominant emissions in environmental and health assessments, respectively.

5.4 Life-Cycle Inventory of Fuels

5.4.1 Liquefied Petroleum Gas (LPG)

According to the Indian government's National Family Health Survey 4 (NFHS-4), between 2015 and 2016, 24% of rural households in India used clean cooking fuel (including electricity, LPG, natural gas, and biogas). According to the National Sample Survey, LPG accounts for an estimated 25.2% of cooking fuel use in India (Cashman et al. 2016). The modeled LPG system includes 1) Extraction/Production 2) Refinement 3) Transportation/Distribution and 4) Use Phase (Cooking) for a 70:30 butane:propane mix. Crude oil and natural gas extraction are modeled with India-specific aggregate processes within the GaBi extended database. These aggregate models include assumptions regarding disposal of sludge and tailings (crude oil) and natural gas leakage and effluents (natural gas). However, these auxiliary processes are not modeled separately. Transportation assumptions from refinery/fractionating plant to bottling facility, emissions from the bottling process and transportation to distributors are modeled after Singh, Gundimeda, and Stucki (2014). LPG is assumed to travel by electric train (40%), diesel train (20%) and heavy duty truck (40%) across distances of 1000 km, 1000 km and 1000 km (500 km in 2 directions), respectively, to reach the bottling facility from refinement/fractioning. Transport from the bottling plant to distributor is assumed to use a heavy duty truck with a 2-way trip of 750 km in each direction. Use phase estimates are to be drawn from the cooking fuel literature (Singh, Gundimeda, and Stucki 2014, Smith 2000).

5.4.2 Biomass

Biomass accounts for an estimated 66% of household cooking fuel use in India. Biomass used for cooking fuels in India predominantly include firewood and animal manure/dung.

Wood fuels are commonly collected by households in rural areas where woody biomass is prevalent. The collection and labor inventory is excluded from the the bounds of this study. Collected wood is dried in the sun to remove moisture content. Wood fuels are then combusted in traditional mud stoves (chulha). Emissions estimates and stove efficiencies for wood combustion are drawn from the literature (Singh, Gundimeda, and Stucki 2014).

Similarly, manure/dung is collected by households. This collection and labor process is outside the scope of this study. However, in subsequent steps, dung is mixed with straw and left in the sun to dry. Dung fuel is then combusted in traditional mud stoves (chulha). Emissions estimates and stove efficiencies for dung cake combustion is drawn from the literature (Singh, Gundimeda, and Stucki 2014).

5.5 Scenario Modeling

Our model seeks to understand the life-cycle impacts of cooking fuel use as is likely to occur under a set of fuel stacking scenarios at the household level. Using the functional unit of 1 GJ as basis, we model the impacts of generating 1 GJ of useful thermal energy with various shares of LPG and biomass (wood and dung cake) fuels. The prevalence of specific biofuels is region-specific within India, as indicated by regional access to woody biomass or livestock dung. As shown in **Figure 2** below, the status quo case according to the published literature is that households with LPG connections still get roughly half of their cooking energy from biofuels, as represented by status quo scenarios 5 and 6. Scenarios 1 through 3 demonstrate the impacts of 100% adoption of each of the three fuel types. Scenario 4 provides an impractical but useful picture of the impacts of equal adoption of each fuel type. Scenarios 7 and 8 represent an almost complete adoption of LPG, with a family still using biomass for occasional tasks. Scenarios 9 and 10 represent a likely interim step to complete adoption given the status quo where LPG use increases to 66% and biomass is used roughly 33% of the time for various cooking tasks. These various LPG use cases are formulated to give us an idea of the health and environmental impacts as we move from the 50/50 status quo to complete adoption.

User Behavior :
Fuel Stacking Scenarios

Status Quo

Scenario 1	100 %	0 %	0%
Scenario 2	0 %	100 %	0 %
Scenario 3	0 %	0 %	100 %
Scenario 4	33 %	33 %	33 %
Scenario 5	50 %	50 %	0 %
Scenario 6	50 %	0%	50%
Scenario 7	85 %	15 %	0 %
Scenario 8	85 %	0 %	15 %
Scenario 9	66 %	33 %	0 %
Scenario 10	66 %	0 %	33 %

Figure 2. User Behavior: Fuel Stacking Scenarios. Displayed are the 10 fuel stacking scenarios analyzed in the study. Different combinations of LPG, wood, and dung were considered. It is assumed that the status quo for stacked fuel usage is 50% LPG/50%Wood or 50%LPG/50%Dung.

6. Results and Findings

Our impact assessment relies on a broad characterization factor calculation using the 18 ReCiPe midpoint categories: 1) Agricultural Land Occupation 2) Climate Change 3) Fossil Depletion 4) Freshwater Ecotoxicity 5) Freshwater Eutrophication 6) Human Toxicity 7) Ionizing Radiation 8) Marine Ecotoxicity 9) Marine Eutrophication 10) Metal Depletion 11) Ozone Depletion 12) Particulate Matter Formation 13) Photochemical Oxidant Formation 14) Terrestrial Acidification 15) Terrestrial Ecotoxicity 16) Urban Land Occupation 17) Water Depletion. We explicitly left out an 18th category - Land Use and Transformation due to our lack of understanding of the negative values that were calculated. We did not consider this category important enough to our findings to distract from our primary results. ReCiPe has three implementations: an Optimistic Individualist approach (I), an Egalitarian approach (E) and a Hierarchist approach (H) - which is considered the consensus scientific method. While all three applications of ReCiPe have some philosophical justification, we chose the consensus approach for our initial findings.

Our broad impact assessment results using the ReCiPe Hierarchist methodology clearly demonstrate the differential impact of upstream emissions with regard to LPG as compared to dung and wood fuels. In all categories save for Global Warming, Particulate Matter Formation and Photochemical Oxidant Formation, the upstream LPG processes dwarf the cooking stage emissions of wood and dung (see **Figure 3)**. The remainder of our analysis focuses only on comparing Global Warming Potential and Particulate Matter Formation, as these were deemed the most important distinguishing categories for comparison of environmental and health impacts. We additionally examine our life-cycle inventory results for the primary contributors to those categories - carbon dioxide and PM2.5, respectively.

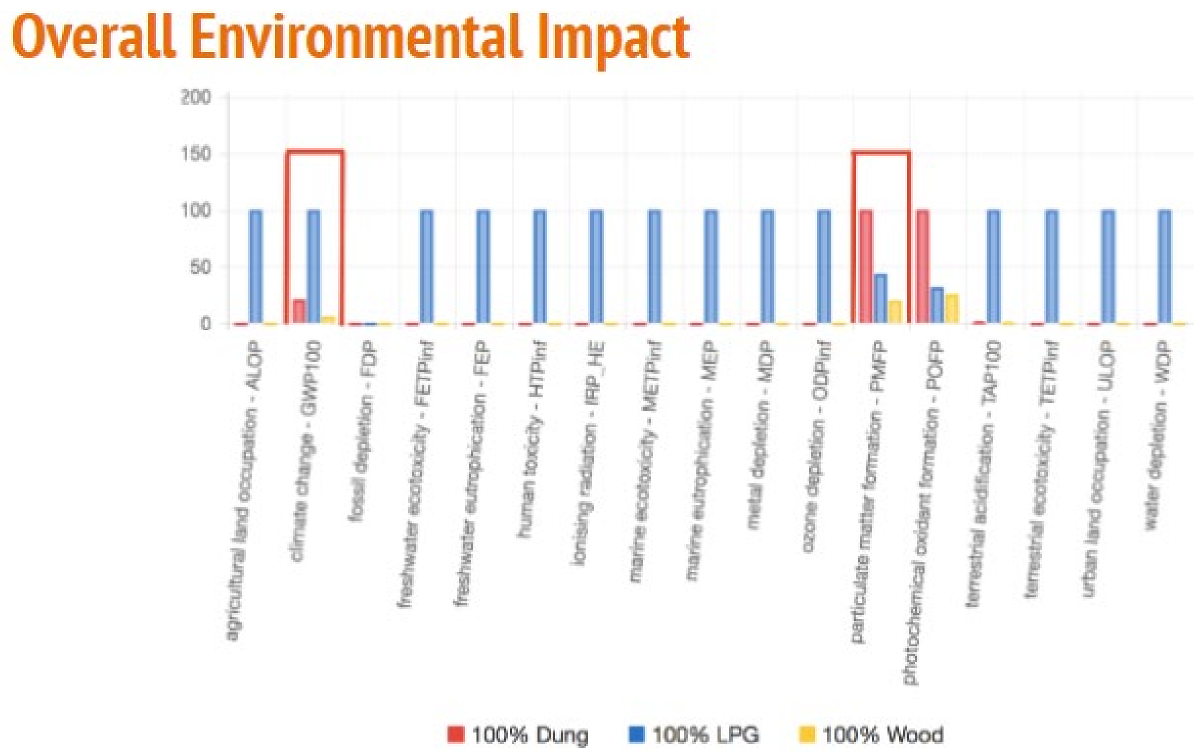

Figure 3. Overall Environmental Impact. Displayed is the overall environmental impact of the three 100% fuel scenarios pertaining to 17 environmental impact categories classified by the ReCiPe impact assessment methodology.

We first examined the broad categories of global warming potential and particulate matter formation, which include measures of multiple criteria pollutants that contribute to these impacts. It is clear that LPG demonstrates the largest global warming potential (measured in tons of carbon dioxide equivalent). Dung registers 90% less global warming potential, and wood fuel emits as little as 5% of the same global warming emissions in our model. With regard to particulate matter formation (measured in tons of PM10 equivalent), the impact of fuel dung far outweighs that of LPG or wood. However, LPG is still responsible for roughly 45% of the impact level as dung. Wood registers a significant but much smaller 20% relative to dung emissions. These relative impacts can be seen in **Figure 4** below.

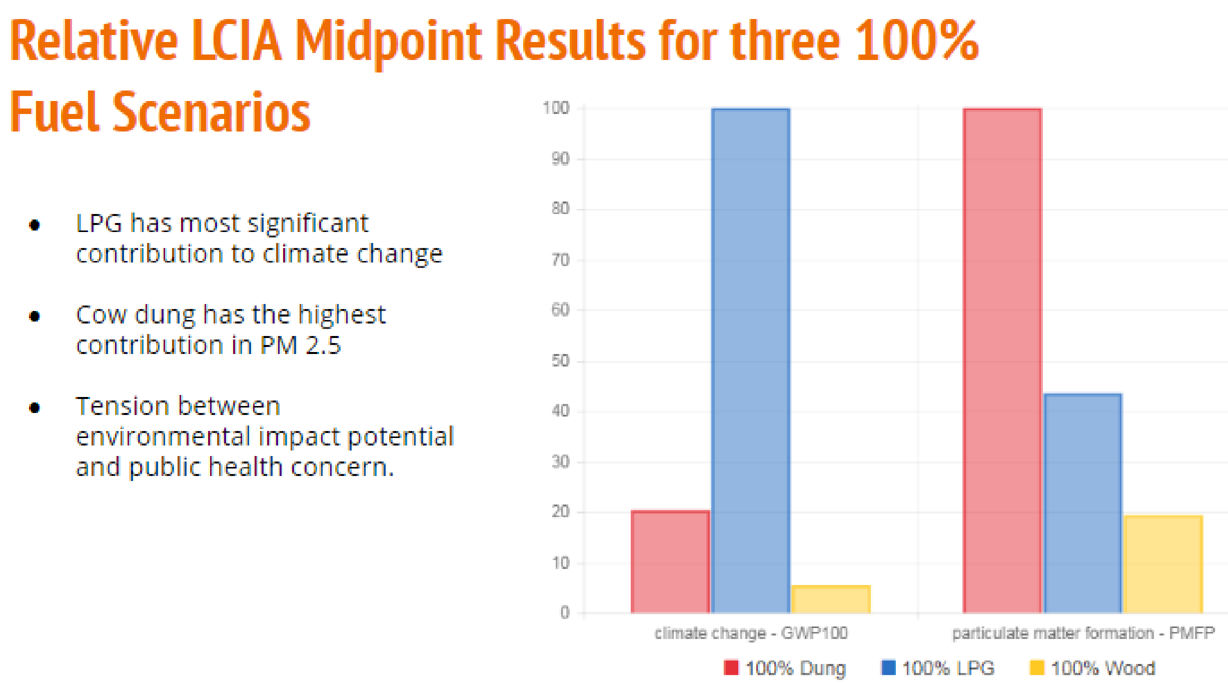

Figure 4. Relative LCIA Midpoint Results for three 100% Fuel Scenarios. Displayed are the percentages of the LPG, wood and dung fuel scenarios relative to the the largest contributing scenario for both climate change as measured by global warming potential (GWP100) and particulate matter formation PMFP.

Next, we focus on carbon dioxide and PM2.5 as the specific pollutants that contribute most to our global warming and particulate formation categories. Much of LPG's carbon dioxide and particulate emissions originate in upstream processes, before the localized cooking process. **Figure 5** below illustrates these emissions grouped by sector of the LPG supply chain.

The sections are delineated as follows:

1) Auxiliary Energy - includes electricity production for all supply chain processes, fuel oil production, diesel production and propane production. These processes consider the aggregate production of energy carriers for downstream processes and the necessary transportation and effluent disposal stages.
2) LPG Bottling
3) Fuel Extraction - includes both crude oil production and natural gas production.
4) Refinement/Fractioning - includes both processes that turn raw crude and natural gas into LPG end-product.
5) Cooking
6) Transportation - included as a category but this stage demonstrated negligible impact in our assessment.

Our initial assessment clearly shows that upstream auxiliary energy production and LPG bottling make up the vast majority of both carbon (1,600 kg/GJ and 1,100 kg respectively) and particulate matter emissions (2 kg and 1.8 kg respectively) for LPG. The production of crude oil and natural gas for LPG also showed significant particulate matter (.152 kg) and carbon (540 kg) impacts, although to a much lesser degree.

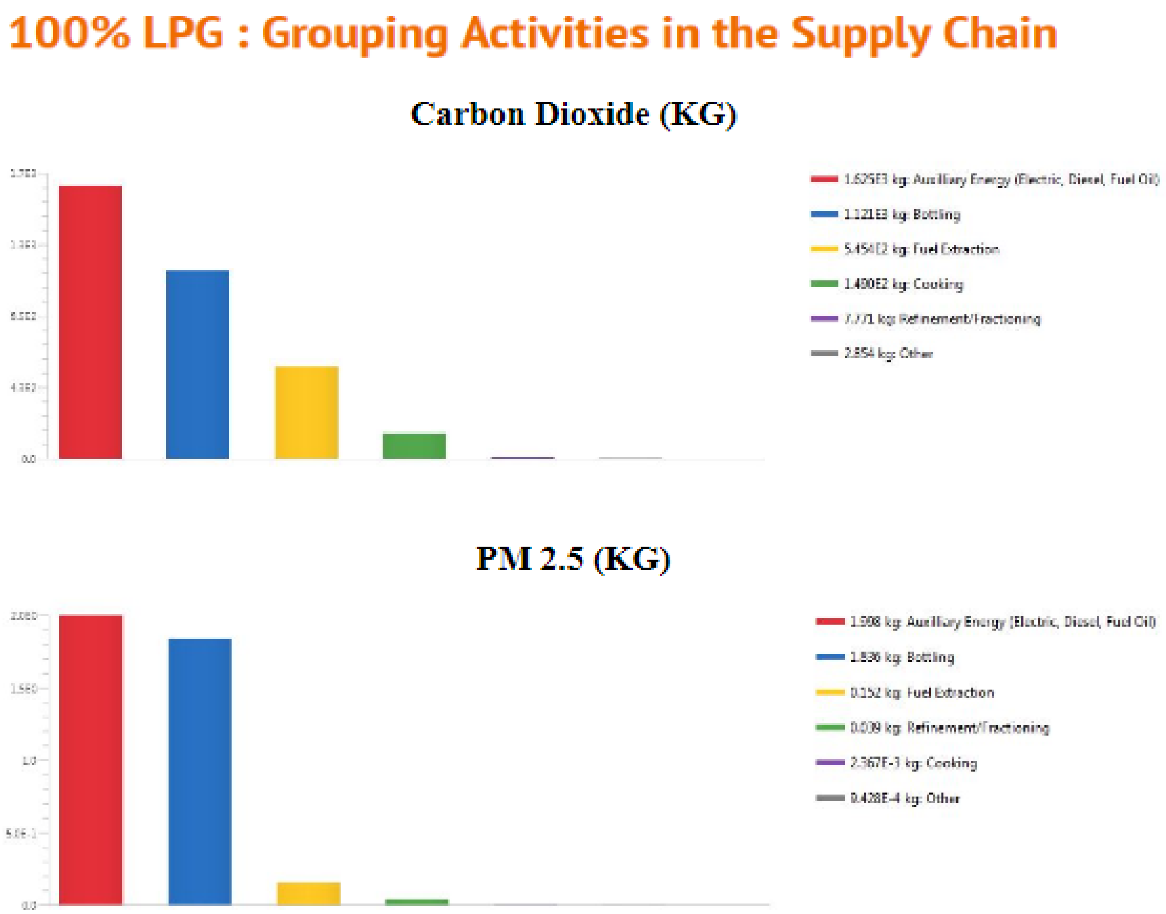

Figure 5. 100% LPG: Grouping Activities in the Supply Chain. Displayed are the per process kilograms of PM2.5 and CO2 emitted as part of LPG production.

Our results are further broken down by individual process contribution to carbon dioxide and PM2.5 across our ten household scenarios. Notably, only the cooking process is included in this model with regard to dung and wood contributions to scenario emissions. By contrast, the full supply chain of LPG appears in the results.

By far, the 100% LPG scenario is the most carbon dioxide intensive scenario. **Figure 6** shows that roughly 3,500 kg of carbon dioxide is produced across the scenario supply chain, with the vast majority originating in electricity production, LPG bottling and crude oil production. Negligible amounts are produced in the cooking stage. Dung (roughly 1,000 kg) produces the highest carbon dioxide emissions in the cooking stage, followed by wood (roughly 500 kg). LPG dominates the mixed fuel scenarios, and the status quo cases of 50/50 LPG/Biomass still emit large quantities of carbon dioxide.

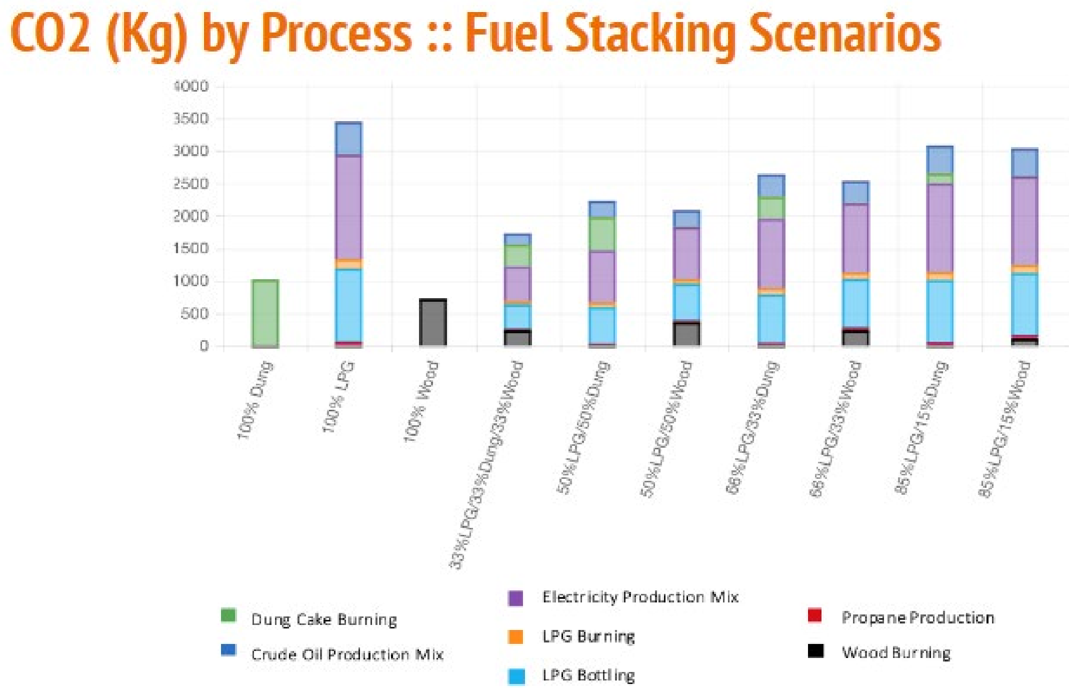

Figure 6. CO2 (Kg) by Process: Fuel Stacking Scenarios. Displayed are the quantities for total CO2 emitted per GJ of cooking energy produced among the 10 tested fuel-stacking scenarios. Total CO2 emitted for each scenario is color-coded as seen in the legend.

The situation is quite different for particulate matter emissions. As seen in **Figure 7**, the cooking phase of dung fuel dominates PM2.5 emissions (at 5 kg). LPG comes in a close second (at 4 kg). However, almost all of LPG's PM2.5 emissions occur upstream and contribute to ambient pollution while dung is all emitted within the household. Much like carbon emissions, PM2.5 emissions from LPG primarily originate in the electricity production and bottling phases. Wood cooking has a much lower PM2.5 emissions profile than either dung or LPG. However, it also releases all of its emissions in the household cooking stage of the supply chain. In the mixed fuel scenarios, it is clear that even small amounts of dung in the mix produce significant household PM2.5 and when mixed with LPG, all mixes contribute greatly to overall PM2.5. Only 100% LPG and 85% LPG/15% Wood scenarios show significant reductions of household PM2.5 from the base case. This has important policy implications, which will be discussed later.

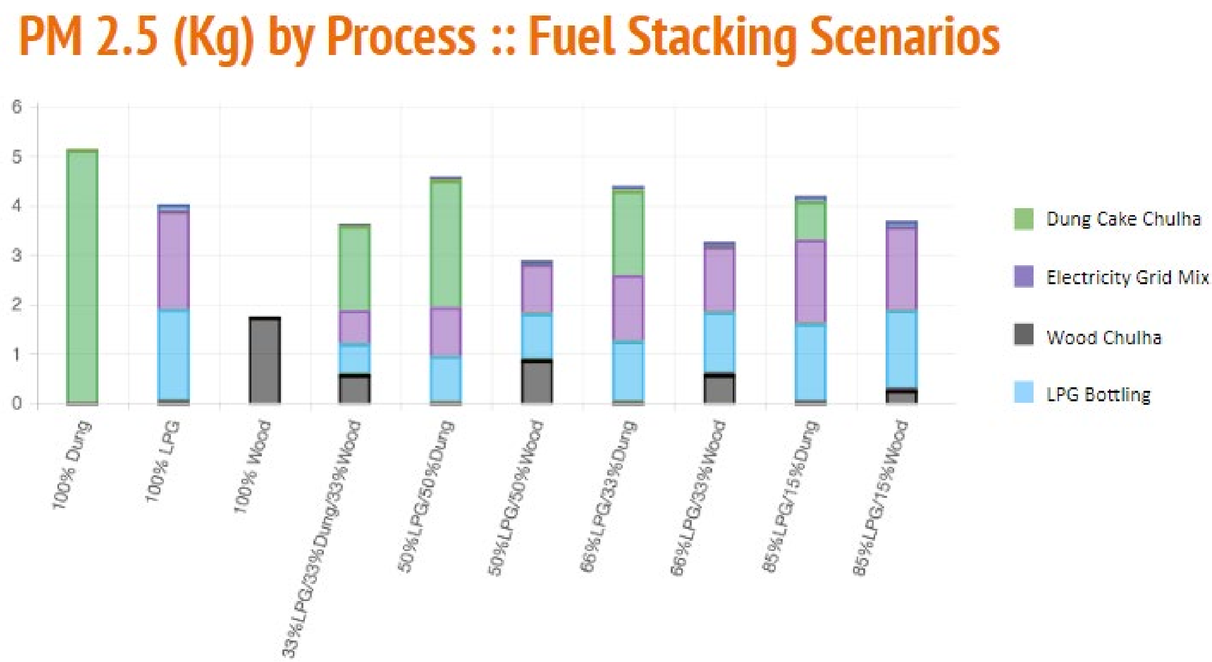

Figure 7. PM2.5 (Kg) by Process: Fuel Stacking Scenarios. Displayed are the quantities for total PM2.5 emitted per GJ of cooking energy produced among the 10 tested fuel-stacking scenarios. Total PM2.5 emitted for each scenario is color-coded according to the legend.

6.1 Human Exposure to Household Air Pollution

Owing to time and resource constraints, we were unable to complete a highly detailed analysis of the potential health impacts of our various cooking fuel scenarios. In consultation with Ajay Pillarisetti, a postdoctoral scholar in UC Berkeley's Household Energy, Climate, and Health Research Group, we opted to use the World Health Organization (WHO) Homes Monte Carlo Box Plot simulator[1] to make a precursor calculation of the expected human exposure to PM2.5 emissions using eight of the most likely fuel scenarios.

The simulations were run using the model's standard values for household characteristics based on WHO testing guidelines.

Air Changes / Hour (hour-1) - **Mean 24 SD 6**
Kitchen Volume (m3) - **Mean 28 SD 10**
Ambient Concentration (µg/m3) - **Mean 35 SD 1**
Number of Emission Sources - **1**
Ratio of Personal Exposure to Kitchen Concentration - **0.63**
Daily Cooking Time (minutes) - **Mean 252 SD 40**
Percent of Emissions Mixing in Room - **Mean 100 SD 10**

[1] https://householdenergy.shinyapps.io/who_homes/

For ambient concentration (µg/m3) within the household we used the WHO Interim 3 target for annual mean concentrations of household particulates (35µg/m3). This was chosen to represent a realistic "best-case" scenario in which a low concentration of background PM2.5 from sources other than cooking would allow us to more sensitively test the impact of the various fuel scenarios. In reality, the background concentrations of PM2.5 within households are most likely much higher. Results from the analysis are seen in **Figure 8**.

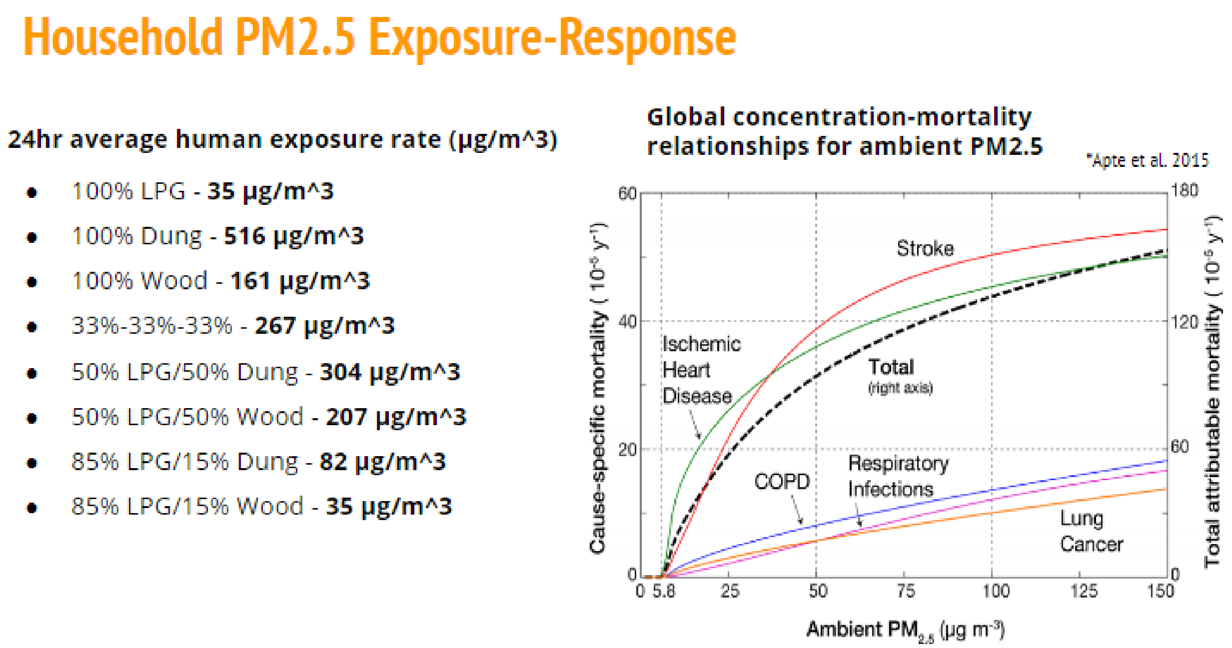

Figure 8. Household PM2.5 Exposure-Response. Displayed are the simulated mean exposure rates to PM2.5 under eight fuel-stacking scenarios alongside the Apte et al. (2015)'s global concentration-mortality relationships for ambient PM2.5. The left vertical axis corresponds to the cause specific mortality correlated to five outcomes (solid lines). The right vertical axis corresponds to the total PM2.5 attributable mortality for the five outcomes (dashed line).

Of the tested scenarios, only the case of 100% LPG and 85% LPG/15% Wood yielded 24-hour exposure rates less than the Interim 3 target of 35µg/m3. All of the remaining scenarios (apart from the case of 85% LPG/15% Dung) tested much higher with concentrations well above 100 µg/m3.

The concentration-mortality relationship for exposure to PM2.5 is a monotonically increasing function in which cause-specific mortality increases with ambient PM2.5 concentration. The trend's decreasing slope suggests that the largest changes in cause-specific mortality come from exposure to PM2.5 at lower concentrations. As the concentration of PM2.5 increases, cause-specific mortality increases at a reduced rate.

The shape of the mortality-relationship for PM2.5 suggests that all scenarios apart from 100% LPG and 85% LPG/15% Dung remain above the concentration window of 0 - ~100µg/m3 most impactful on cause-specific mortality. This suggests that arguably unless 100% uptake of LPG is achieved, the reduction in mortality and health risks due to household PM2.5 exposure may not be enough to justify the costs of the massive LPG dissemination policy. This conclusion is supported knowing that household background concentrations of PM2.5 is likely much higher.

Although a rather crude preliminary analysis, it reveals important information that we suspect will be replicated in further testing. The results align with our hypothesis that fuel-stacking scenarios severely limit the effectiveness of the LPG dissemination policy in achieving health relevant impacts. Moving forward, our hope is to create a more detailed simulation of emissions exposure working with data from the Household Energy, Climate, and Health Research Group.

Furthermore, we hope to expand the analysis and delineate between health relevant exposure to particulate matter at the household level and exposure to particulate matter that can be attributed to LPG's upstream processes. Particulate matter emissions from the electricity production mix and LPG bottling process, when adjusted for per/capita exposure, may lessen LPG's overall health benefit relative to wood and dung.

7. Sensitivity Analysis

For our sensitivity analysis, 500 Monte Carlo simulations were conducted for each of 10 designed scenarios in OpenLCA to understand how changing parameters affects the key impact values. The method used probability experiments to obtain a range of impact outcomes given a set of parameter conditions in the life-cycle inventory framework.

Based on the model, the heat delivered to the pot is the last step of the cooking process, which is the result of cookstove efficiency. Other variables, such as the transport distances of fuels in previous stages, also contribute to the total amount of life-cycle emissions. For LPG, the mean stove efficiency is 51% with a 3% standard deviation, while for dung and wood, the mean stove efficiency is 10% with a 2.5% standard deviation. Regarding the transportation distance, we assumed a standard deviation of 20% of the original mean values which ranged between 500 km and 1000 km depending on the transportation stage and vehicle (e.g. electric train, diesel train, and heavy duty truck).

This random sampling was run 500 times for each scenario while varying stove efficiencies and transportation parameters according to a normal distribution. The probability distributions of the two key impact categories, Global Warming Potential and Particulate Matter Formation, are presented in **Figure 9** and **Figure 10**.

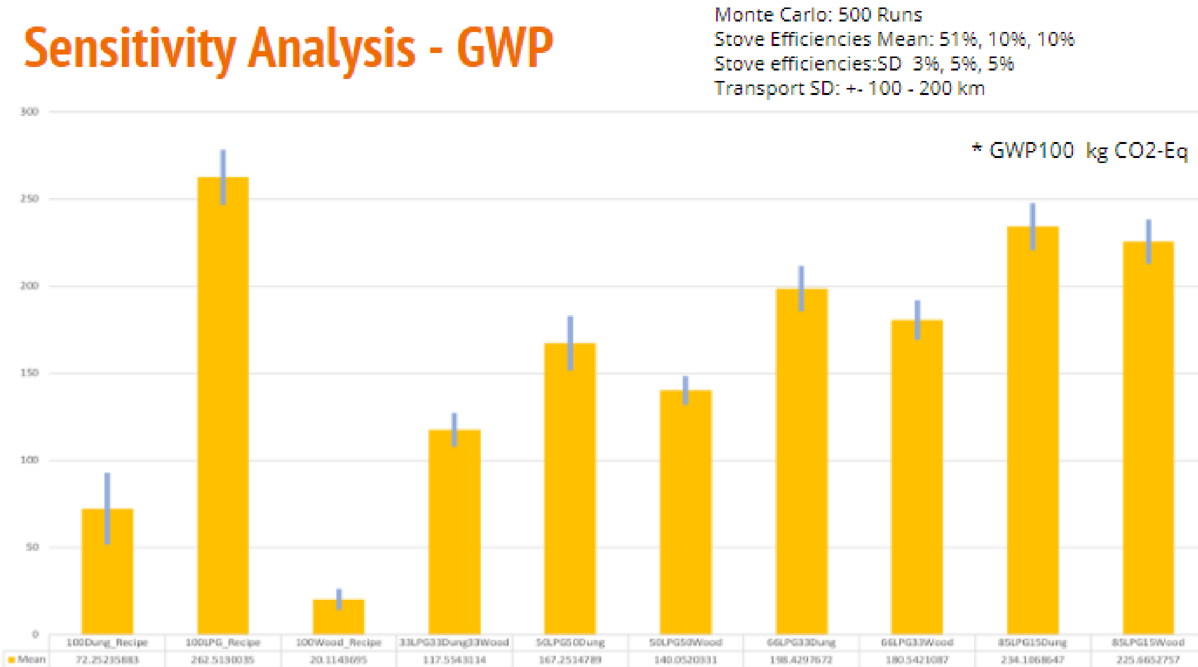

Figure 9. Sensitivity for Global Warming Potential in 10 scenarios, measuring in kg of carbon dioxide equivalent for 100 years. The yellow column is the mean value and the blue bar shows the changing range.

As **Figure 9** shows, the first scenario of 100% Dung has the biggest range. While other scenarios have similar levels, the 100% Wood scenario has the smallest range. And other scenarios with some wood use are relatively less sensitive, showing a decreasing sensitivity from 15% Wood to 100% Wood.

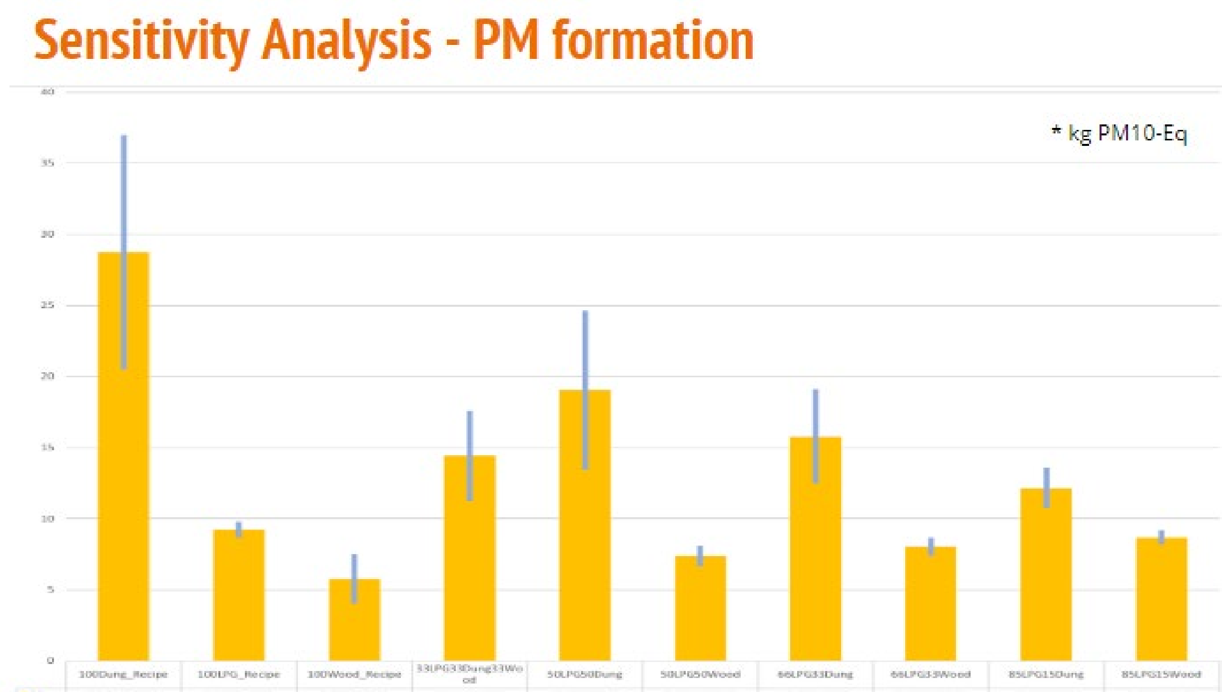

Figure 10. The Sensitivity for particulate matter formation in 10 scenarios, measuring in kg of PM 10 equivalent. The yellow column is the mean value and the blue bar shows the changing range.

Regarding particulate matter formation, the use of dung involves huge uncertainty, and the level depends on how much dung is used in the specific scenario. However, stove efficiency and transport distance have little impact on PM2.5 emissions if wood and, to a lesser degree, LPG is used.

8. Uncertainty Assessment and Management

Information on India's energy sector is fairly abundant. Moreover, interest in cookstoves and cooking fuels in emerging economies is longstanding and much literature exists in this space. Our study makes use of India-specific energy sector data from an established and respected commercial database, the GaBi EcoInvent 3 extended databases. Moreover, we draw from decades of studies on cookstove efficiency and cooking fuel emissions, many of them centered specifically in the India case. Hence, our data confidence is moderately high with regard to upstream and cooking emissions from LPG and cooking emissions from dung and wood fuels.

While we are confident in our data's precision and the representativeness of certain cases within India, it is also true that our data does not represent supply chain conditions in all cases, and this introduces a fair amount of uncertainty to the aggregate supply scenario. For instance, shares of onshore and offshore domestic oil and gas production and the share of imports change over time. Moreover, travel distances are approximations. The transportation fleet and impacts of the LPG supply chain vary greatly across the nation. And cookstoves are made by many processes, leading to variation in stove efficiency, along with other location specific characteristics that affect performance all along the supply chain. Still, we are confident that our base-case is a useful approximation with a good level of confidence despite these uncertainties.

However, with regard to our calculations of PM2.5 exposure, our uncertainty level is quite high. We calculated our numbers using a parameterized box model which can only coarsely approximate the conditions of an average home in India. Specific conditions, such as size of the home, ambient air quality, wind, temperature and air flow are highly variable, and so our certainty in our numbers is much lower.

We have addressed our uncertainty to some degree, as resources and time permitted, by applying a Monte Carlo sensitivity analysis to what we believe are two of our most important uncertain variables: transportation distances and stove efficiency.

Please see **Table 4.** below for the breakdown of our uncertainty matrix.

Table 4. Uncertainty Matrix of Data Categories

Data Quality Table	**Acquisition Method**	**Independence of data supplier**	**Representativeness**	**Temporal Correlation**	**Geographical Correlation**	**Technological Correlation**
Crude and Natural Gas Production	2	1	3	3	1	1

Power Generation and Energy Carrier Production (Electricity, Diesel, Fuel Oil etc.)	2	1	3	3	1	1
Transportatio n	3	1	3	3	3	2
LPG supply chain, refinement and bottling	3	1	3	3	1	1
Dung, Wood, and LPG Cookstove data	2	1	3	2	1	2
PM 2.5 Exposure	5	1	5	2	4	5

9. Interpretation and Discussion of Results

9.1 Potential Household Health Impacts of LPG Under Variable Fuel Stacking Scenarios

Results from our preliminary analysis of human exposure to PM2.5 under eight of the 10 fuel stacking scenarios suggest that unless near 100% uptake of LPG is achieved, the reduction in mortality and health risks due to household PM2.5 exposure may be negligible. Our simulation included a low background concentration of particulate matter consistent with what we considered to be a "best case" scenario. In actuality, variable household characteristics including additional sources of indoor particulate matter emissions and outdoor air pollution penetration likely make the background concentration much higher. For this reason, policy measures that target the contributing factors to indoor air pollution exposure in addition to fuel choice are most likely necessary to achieve relevant health impacts. The shape of the mortality-relationship for PM2.5 suggests that the "last mile" of reduction to emissions exposure is arguably the most important is reducing cause-specific mortality.

An important directive of this research would be to conduct a cost-benefit analysis of *Pradhan Mantri Ujjwala Yojana* that clarifies the value of the reduction in DALYs and mortality as a result of the LPG distribution scheme compared to the USD $1.5 billion budgeted to support the program through March 2019.

Moving forward we hope to expand our analysis by quantifying the health relevant exposure to particulate matter that can be attributed to LPG's upstream processes. Human exposure to particulate matter emissions, as a result of the electricity production mix and LPG bottling process, may discount LPG's superiority as a clean fuel alternative.

It was announced in September that the Indian government was drawing up plans to reduce subsidized fuel costs by blending LPG with methanol and scaling up the production of coal produced domestically (The Economic Times 2018). A reduction in the cost of LPG provision is assumed to be beneficial to customer uptake. However as of yet, there exists no quantification of the relative emissions impact that adding methanol to LPG would have. This serves as additional evidence for the need to research better characterizations of human exposure as a result of ambient emissions of PM2.5 due to LPG production.

9.2 Tradeoffs Between Health and Environmental Impacts with Regard to Cooking Fuel Policy

Our study indicates that the contribution of LPG production and distribution due to global warming potential is significantly higher than that of biofuels. However, the associated risk to human health resulting from exposure to emissions from cooking with biofuels, in particular dung, is disproportionately higher than the risk from LPG. This result is a key point of tension for decision-makers - a critical choice between tackling either a looming public health issue or environmental issue in the short term. The impetus for this policy came from recent assessments on the burden of disease that highlight the scale of air pollution–related health impacts (Lim et al. 2012, Forouzanfar et al. 2015) and the need to address dual burdens from ambient and household air pollution (Balakrishnan et al. 2014). Around 1.5 million premature deaths in India — deaths due to a range of acute and chronic health conditions — are attributable annually to the indoor and outdoor exposures of the population to air pollution (IHME 2015).

Pradhan Mantri Ujjwala Yojana has been championed as supporting public health as well as providing economic and social benefits. While the issues are highly intertwined, the government needs a different plan of action when aiming to lead the transition to cleaner fuels. The focus on remedies for environmental degradation due to LPG production is key. As suggested in the recommendations, it is critical to work towards cleaning India's electricity mix to reduce the global warming potential of LPG.

10. Conclusions and Recommendations

Our analysis points to the need for India's PMUY policy to address the potentially offsetting effects of household fuel-stacking, at least when it comes to reductions of indoor PM2.5 emissions from burning of biomass. This analysis shows that incomplete substitution of LPG for biofuels still produces enough PM2.5 to endanger the health of millions of Indians participating in the subsidized LPG program.

This scenario, however, is different when evaluating the global warming potential of using LPG, dung and wood. In that case, LPG use is by far the bigger producer of CO2 and other greenhouse gases, principally from the production and bottling phases. Wood and dung, by comparison, produce far less CO2 than LPG, at least under current LPG production processes.

With those findings in mind, the Indian government could take two concurrent steps to spread the benefits of the lower PM2.5 emissions of LPG while addressing the sizable greenhouse gas emissions related to production and bottling of LPG.

First, the PMUY program could fully subsidize the purchase of refill canisters of LPG, rather than partly subsidize them as is current practice. As it's designed, the program offers a 1,500 rupee (USD $21) loan to program participants to buy a cookstove and the initial refill canister. Participants must then pay the market price of about 800 rupees for subsequent refill canisters until their loan is paid off. Then, the program partly subsidizes additional canisters. Households are still expected to make up for the difference by paying 300 rupees (USD $4.29) for each canister.

The problem is that price may still prove prohibitive for program participants, with 60 percent of Indians living on less than $3.10 a day. That price gap, in fact, could explain the apparent low canister refill rates described by some politicians and press reports. Fully subsidizing canister refills for the 80 million households in the PMUY program would roughly double the USD $1.5 billion cost of the program to the Indian government.

Cleaning India's electricity grid would also greatly reduce both the global warming and PM2.5 impact of LPG, as well as the impact of all petroleum and natural gas refined products. India's electricity grid is still largely powered by coal - the dirtiest fuel source when it comes to global warming potential. The LPG example shows how decarbonizing electricity has knock-on effects. For one thing, it would make the benefits of the LPG transition less ambiguous, and complement LPG's low PM2.5 emissions.

Finally, at least based on our results, LPG may actually not make the most sense when seen through a global warming potential and PM2.5 lens. No, the winner on both fronts is, in fact, wood, which produces the least amount of CO2 and PM2.5, according to our analysis. It is highly doubtful, however, that Indian public health officials will encourage a return to mass wood burning for cooking and heating in the world's second most populous country. No, the road ahead will surely be to make LPG as clean as possible, both upstream and downstream.

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