Public Investment Cases for Clean Cooking: Nairobi, Kenya and Kathmandu, Nepal

---

Final Report Produced for

CLEAN
COOKING
ALLIANCE

November 2020

Authors:

Dr. Ipsita Das
Duke University Sanford School of Public Policy
Email: ipsita.das@duke.edu

Dr. Marc Jeuland
Duke University Sanford School of Public Policy and Duke Global Health Institute
Email: marc.jeuland@duke.edu

Table of Contents

Executive Summary

Introduction

Approximately 2.8 billion people across the world rely on solid fuels, kerosene, and coal for cooking (International Energy Agency (IEA), International Renewable Energy Agency (IRENA), United Nations Statistics Division (UNSD), World Bank, and World Health Organization (WHO) 2020). Burning these polluting fuels in inefficient stoves produces household air pollution (HAP) that adversely affects human health, environmental quality, and the climate (Anenberg et al. 2013; Lim et al. 2013; Martin et al. 2014; Myhre et al. 2013). Approximately 4 million premature deaths occur each year due to exposure to HAP (WHO 2018). Sub-Saharan Africa (SSA) and South Asia (SA) have the highest global shares of polluting fuel users (77% and 61%, respectively) and therefore bear a disproportionate burden of HAP impacts (Bonjour et al. 2013). Despite progress in dissemination and efforts to roll out and scale interventions worldwide, these interventions have not always resulted in significant behavior change or positive impacts, and high population growth in these regions has stalled the decline in solid fuel users as a share of the population (IEA, IRENA, UNSD, World Bank, and WHO 2020). The literature on the economics of such technologies, from the perspective of households and communities, suggests that private incentives play an important role in these continued challenges. Put differently, the net benefits from switching to cleaner technology are not always positive for individual users.

Global progress towards clean cooking perhaps has been more rapid in urban areas, but rising ambient air pollution levels in most major cities in SSA and SA necessitate multipronged mitigation strategies that both continue to combat HAP generation and also address other urban air pollution sources. Previous cost-benefit analyses of clean cooking primarily have been conducted at the regional (Hutton et al. 2007; Larsen 2014) or household levels (Jeuland and Pattanayak 2012; Jeuland, Tan Soo, and Shindell 2018). None of these analyses have considered the urban context specifically or been carried out at the city level. In addition, no prior analyses have applied a framework based on the economic theory of demand, to examine how specific policy interventions (such as subsidies or other incentives) might shift the private net benefits of different cooking transitions.

This report presents a framework and results from an urban cost-benefit and policy analysis, applied in two contrasting but important settings for studying urban cooking transitions. These cases – in Nairobi, Kenya and Kathmandu, Nepal – were selected to provide insights into the differences between SSA and SA, the two regions with the greatest persistence of solid fuel use. While every city is unique, these two examples demonstrate important differences between their regions, most notably related to the fuel mix that typically is used by households: charcoal and kerosene in SSA, and firewood in SA. The two cases of Nairobi and Kathmandu also demonstrate, among clean options, different potentials for LPG, ethanol, and electric cooking.

Approach

We extend an existing framework to allow for such analysis in Nairobi and Kathmandu (Jeuland, Tan Soo, and Shindell 2018). In each policy site, we first outline baseline conditions, and discuss the hypothetical health, well-being, environmental, and climate implications of fully transitioning to various potential cleaner cooking solutions. In the subsequent policy analysis for each location, we account for partial uptake and use of cleaner cooking choices, and shift to a description of the net benefits (social and private) of each transition under five real-world policy interventions, given the limited evidence about the effectiveness of such strategies (Table E1). The interventions include stove subsidy, combined stove and fuel subsidy, combined stove subsidy and financing, combined stove subsidy and behavior change communication (BCC), and lastly, a polluting fuel ban (Table E2). Our results are meant to inform policy-makers about the relative merits of these different strategies for accelerating clean cooking transitions in these settings.

Table E1. Summary of cooking transitions

Transition No.	Nairobi	Kathmandu Valley
1	Traditional charcoal to charcoal improved cookstoves (ICS)	Traditional firewood to natural draft ICS
2	All charcoal to liquefied petroleum gas (LPG)	Traditional firewood to LPG
3	Kerosene to LPG	Traditional firewood to electricity
4	All charcoal to ethanol	LPG to electricity
5	Kerosene to ethanol	Electricity to LPG

Table E2. Summary of policy interventions

	Transitions applicable	
Policy Intervention	**Nairobi**	**Kathmandu Valley**
Stove subsidy only	All	All
Fuel subsidy (w/stove subsidy)	All except traditional charcoal to charcoal ICS (T1)	All except traditional firewood to natural draft ICS (T1)
Stove financing (w/stove subsidy)	All	All
Behavior change communication (w/stove subsidy)	All	All
Polluting fuel ban	All	All except LPG to electricity (T4) and electricity to LPG (T5)

Similar to Jeuland and Pattanayak (2012) and Jeuland, Tan Soo, and Shindell (2018), we develop equations that allow calculation of the costs and benefits associated with various clean cooking choices. We also incorporate accounting of the contribution of domestic fuel burning to ambient $PM_{2.5}$[1] concentrations and exposures. This is particularly relevant in urban areas in low- and middle-income

---

[1] The United States Environmental Protection Agency defines $PM_{2.5}$ to include "fine inhalable particles, with diameters that are generally 2.5 micrometers and smaller" (United States Environmental Protection Agency 2020).

countries, where exposures to pollution are not as strongly influenced by household cooking as in rural environments, but are substantial nonetheless. Two additional and key modifications are to allow aggregation of costs and benefits at the city level, and to characterize the costs and benefits of specific policies, based on the likely behavioral responses they would engender. Finally, we include several transitions that were not considered in previous analyses, crafted in response to feedback obtained during our in-country stakeholder interviews about the most relevant options to consider in each city. The unit of analysis for our calculations is the whole of Nairobi city (in Case 1) and the whole of Kathmandu Valley, including the cities of Kathmandu, Lalitpur, and Bhaktapur (in Case 2).

Data Sources and Model Parameters

The model was parameterized using a variety of secondary datasets relevant to energy used in our study locations, supplemented by global literature as previously presented in Jeuland, Tan Soo, and Shindell (2018). We also conducted more focused data collection in 2019, among 354 households from four informal settlements in Nairobi, and 360 households from peri-urban areas in the Kathmandu Valley. In both sites, in addition to asking questions aimed at specifying parameters that are not available in the literature, we included a stated preference experiment to assess households' price sensitivity for proposed transitional (firewood, charcoal, and kerosene) or clean cooking (LPG, electricity, and ethanol) technologies, which was crucial for our eventual prediction of the effects of pricing policies, in the investment cases analyses.

Results

Our results show that in each location, the most cost-beneficial and practical intervention varies depending on the polluting or transitional cooking technology that is being replaced. We applied several criteria to assess the relative value of different solutions: (a) positive and high social net benefits (to generate social value); (b) positive private net benefits (to foster adoption of the solutions); (c) modest cost burden on the government; and (d) pro-poor outcomes. We also considered logistical aspects.

Solutions for Nairobi, Kenya

From the social net benefits perspective, the combined stove subsidy and financing policy option is the most cost-beneficial for transitions from traditional charcoal (to improved cook stoves [ICS] charcoal) and kerosene (to LPG and ethanol), while a charcoal ban appears most cost-beneficial for the transitions from all charcoal stoves (Table E3). However, a charcoal ban is logistically difficult and not pro-poor, so a stove subsidy with financing is likely more appropriate. Fuel subsidies for ethanol and LPG also are clearly attractive privately, but these have public costs that are an order of magnitude higher than the other interventions (Figure E1). In each of the five transitions, government subsidy costs in the stove subsidy plus financing option are far lower, though this policy is more costly than the stove subsidy or stove subsidy plus BCC approaches, because it reaches more customers. Because of the large number of households using kerosene, transitions from this dirty fuel to LPG are potentially the most favorable in Nairobi. A kerosene-to-ethanol transition also has high social net benefits, but the ethanol market is underdeveloped at this time and few of Nairobi's households use the fuel. Considerable work would be necessary to make this a viable transition. Transitions away from charcoal also are attractive and more likely to be pro-poor, though they affect a smaller fraction of households. With a stove subsidy and financing policy, this transition to LPG would have positive and significant monthly social and private net benefits, and the cost to the government would remain modest.

It is essential to remember that, though the stove and fuel subsidy policies are considered pro-poor based on a metric of private benefits that considers the most salient (non-health) benefits, subsidies for clean fuels are difficult to target in practice, and therefore they end up mostly benefiting higher income households (Kar et al. 2019; Pachauri 2019). As a result, an efficient targeting instrument that reaches the poor preferentially could be especially helpful in reducing the high public costs of clean fuel subsidies in Nairobi (Figure E1), while at the same time, being pro-poor. Examples of such an instrument include a means-tested cash transfer conditioned on household fuel use, or alternatively, a subsidy targeted specifically at the poor based on easily-applied eligibility criteria, like the LPG subsidy in India.

Given the relatively good performance of a stove subsidy and finance policy, it also is worth comparing the combination's likely effects on the overall potential of the transitions it would aim to facilitate. This policy option achieves only about 18% of the potential of the transition to charcoal ICS, and between 29% and 40% of the potential of the transitions from charcoal and kerosene to clean fuels. As such, some benefits would be left on the table, and additional instruments could be necessary to capture more of these transitions' benefits.

Solutions for Kathmandu Valley, Nepal

The transitions to electricity from firewood and LPG yield considerably higher social net benefits than movement to LPG by firewood users (Table E3). For the firewood-to-electricity transition, the highest monthly social net benefits are realized with a ban on firewood. For the LPG-to-electricity transition, benefits are greatest with a stove subsidy and financing policy. The high enforcement costs of a ban and the reality of stove stacking (combined use of traditional, improved and clean stove technologies) could render a firewood ban challenging, though the dynamics of this fuel use, which is mostly collected, are notably different than for charcoal in Nairobi, where that fuel is mainly purchased. An alternative to a ban that delivers nearly the same net social benefits is the combined stove and fuel subsidy (Figure E2), but this policy also would face significant practical challenges, due to the difficulty of targeting electricity subsidies specifically for cooking purposes (given electric appliances within the household unrelated to cooking). Transitioning existing firewood users to LPG appears to have limited effects, and likely would require subsidizing LPG. This would be justified only by effective targeting to low-income populations, given the policy's negative social net benefits.

An LPG-to-electricity transition is intriguing for Kathmandu, because it has a potential to generate large social and private benefits. The two preferred interventions for supporting this transition appear to be the stove subsidy and financing policy, and a combined fuel-and-stove subsidy. However, the latter likely would face substantial implementation hurdles, for the reason discussed previously: targeted electricity subsidies for cooking would appear impractical without new technology. Similar to the case of fuel subsidies in Nairobi (in that case, for LPG or ethanol), electricity subsidies also would be difficult to target to the poor. Also, while transitions to electricity appear favorable, electricity as a primary cooking source currently is rare in Kathmandu Valley. BCC campaigns likely would be necessary to educate households about the benefits of cooking with electricity, from a cost and energy security perspective.

Finally, comparing the actual policies to the potential of the electricity transitions in Kathmandu Valley, we note that the firewood-to-electricity transition would achieve about 37% of the transition potential under the stove subsidy and financing option. For the LPG-to-electricity transition, the stove subsidy plus finance option would reach 24% of the potential of this transition.

Table E3. Summary of cooking transitions in Nairobi and Kathmandu Valley (all outcomes reported at city scale, in U.S.$/month)

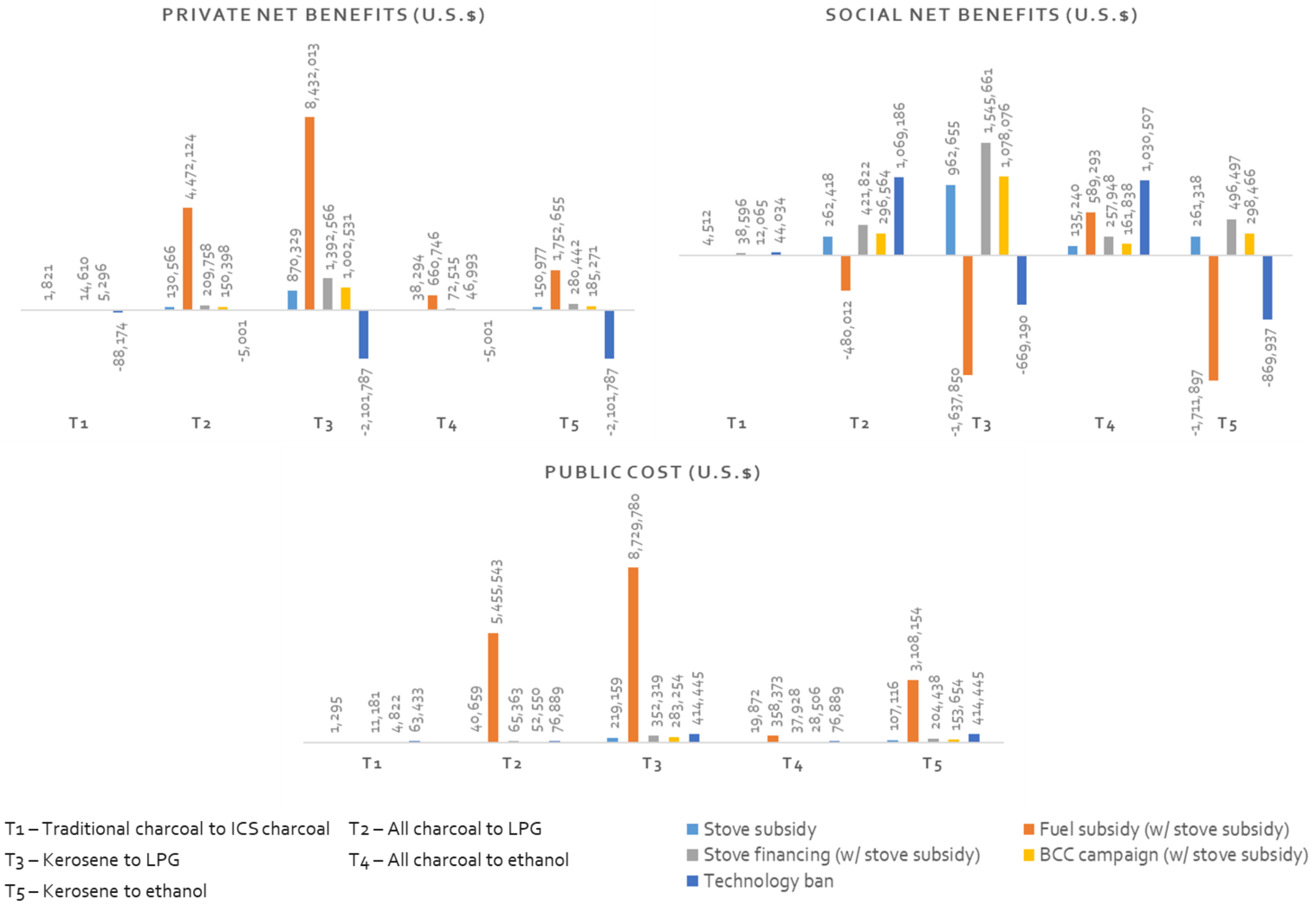
	Social net benefits (Net Present Value or NPV)	**Private net benefits (NPV)**	**Public cost**	**Most pro-poor (NPV – private net benefits without health)**
		Panel A: Nairobi transitions		
Transition 1: Traditional charcoal to charcoal ICS	1. Technology ban ($44,034) **2. Stove financing plus subsidy ($38,596)**	**1. Stove financing plus subsidy ($14,610)** *2. BCC campaign with stove subsidy ($5,296)*	1. Stove subsidy ($1,295) *2. BCC campaign with stove subsidy ($4,822)*	**1. Stove financing plus subsidy ($11,495)** *2. BCC campaign with stove subsidy ($4,247)*
Transition 2: All charcoal to LPG	1. Technology ban ($1.1 million) **2. Stove financing plus subsidy ($421,822)**	*1. Fuel plus stove subsidy ($4.5 million)* **2. Stove financing plus subsidy ($209,758)**	1. Stove subsidy ($40,659) 2. BCC campaign with stove subsidy ($52,550)	*1. Fuel plus stove subsidy ($3.2 million)*
Transition 3: Kerosene to LPG	**1. Stove financing plus subsidy ($1.5 million)** *2. BCC campaign with stove subsidy ($1.1 million)*	*1. Fuel plus stove subsidy ($8.4 million)* **2. Stove financing plus subsidy ($1.4 million)**	1. Stove subsidy ($219,159) *2. BCC campaign with stove subsidy ($283,254)*	*1. Fuel plus stove subsidy ($6.9 million)* **2. Stove financing plus subsidy ($610,756)**
Transition 4: All charcoal to ethanol	1. Technology ban ($1 million) **2. Fuel plus stove subsidy ($589,293)**	**1. Fuel plus stove subsidy ($660,746)** 2. Stove financing plus subsidy	1. Stove subsidy ($19,872) 2. BCC campaign with stove subsidy ($28,506)	None

		($72,515)		
Transition 5: Kerosene to ethanol	**1. Stove financing plus subsidy ($496,497)** *2. BCC campaign with stove subsidy ($298,466)*	*1. Fuel plus stove subsidy ($1.7 million)* **2. Stove financing plus subsidy ($280,442)**	1. Stove subsidy ($107,116) *2. BCC campaign with stove subsidy ($153,654)*	*1. Fuel plus stove subsidy ($721,126)*
Panel B: Kathmandu Valley transitions				
Transition 1: Traditional firewood to natural draft ICS	1. Stove financing plus subsidy ($74,761) **2. BCC campaign plus stove subsidy ($44,750)**	**1. BCC campaign with stove subsidy ($25,780)** *2. Stove subsidy ($21,112)*	*1. Stove subsidy ($20,105)* **2. BCC campaign with stove subsidy ($32,490)**	**1. BCC campaign with stove subsidy ($8,876)** *2. Stove subsidy ($7,269)*
Transition 2: Traditional firewood to LPG	**1. Stove subsidy ($1,266)**	*1. Fuel plus stove subsidy ($2.6 million)*	**1. Stove subsidy ($15,615)** 2. BCC campaign with stove subsidy ($24,582)	*1. Fuel plus stove subsidy ($2.5 million)*
Transition 3: Traditional firewood to electricity	1. Technology ban ($167,946) **2. Fuel plus stove subsidy ($165,612)**	**1. Fuel plus stove subsidy ($308,932)**	1. Stove subsidy ($37,447) 2. BCC campaign with stove subsidy ($50,113)	**1. Fuel plus stove subsidy ($173,502)**

Transition 4: LPG to electricity	**1. Stove financing plus subsidy ($1.45 million)** *2. Fuel plus stove subsidy ($1.4 million)*	*1. Fuel plus stove subsidy ($2 million)* **2. Stove financing plus subsidy ($1.4 million)**	1. Stove subsidy ($67,287) 2. BCC campaign with stove subsidy ($120,080)	*1. Fuel plus stove subsidy ($2 million)* **2. Stove financing plus subsidy ($1.4 million)**
Transition 5: Electricity to LPG	None	**1. Fuel plus stove subsidy ($3.7 million)**	1. Stove subsidy ($137) 2. BCC campaign with stove subsidy ($215)	**1. Fuel plus stove subsidy ($3.7 million)**

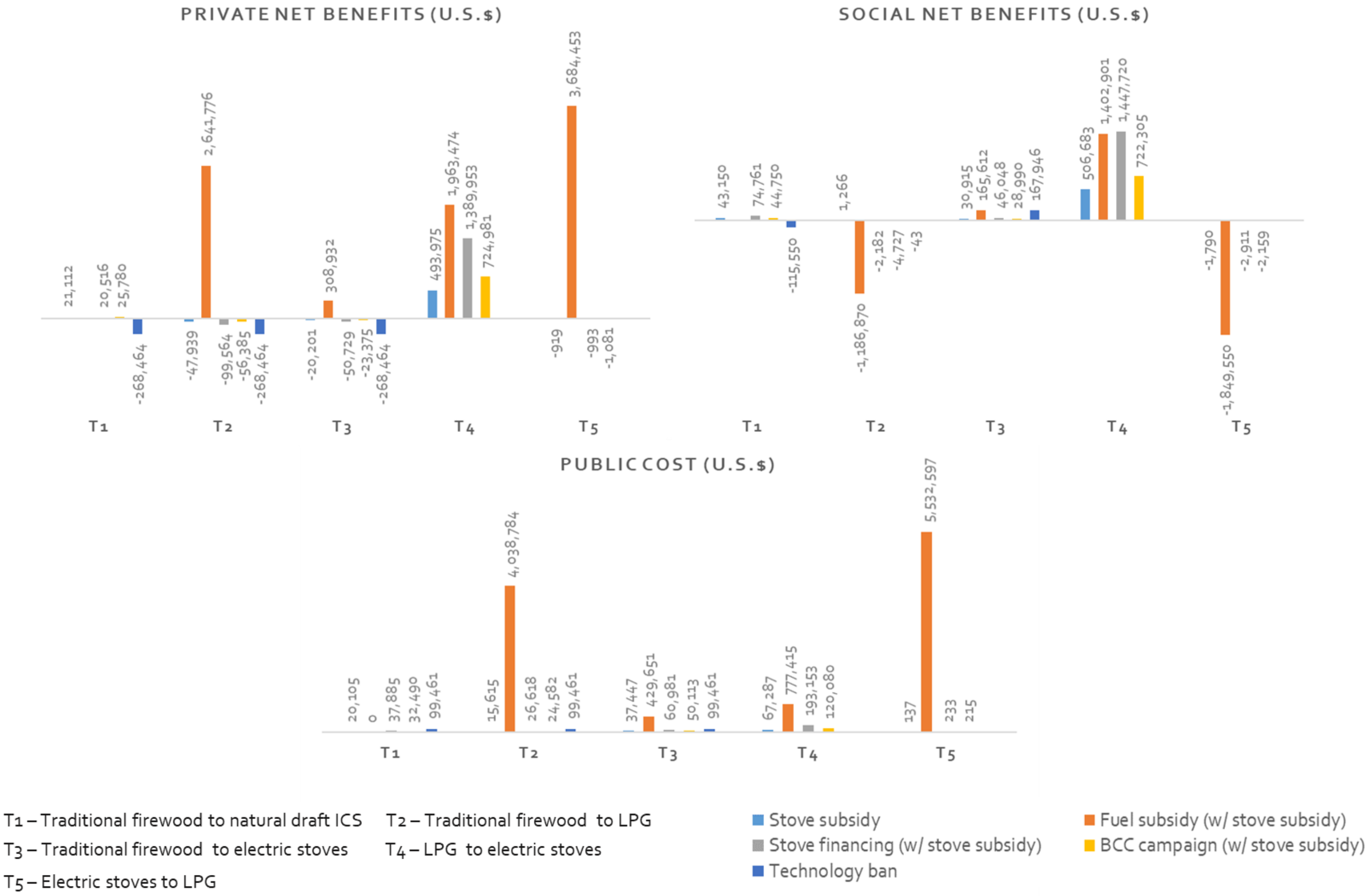
Note: In each row, the intervention that is bolded appears most often and highest in rank (with preference given to overall social benefits in the case of ties), while italicized interventions appear equally often or second most often and are highly ranked.

Figure E1. Comparison of relative performance of policies for fostering different cooking transitions in Nairobi



Note: For the stove and fuel subsidies, the graph shows the potential at the default levels specified in the Analytical Framework section.

Figure E2. Comparison of relative performance of the policies for fostering different cooking transitions in Kathmandu Valley



Note: For the stove and fuel subsidies, the graph shows the potential at the default levels specified in the Analytical Framework section.

Conclusion

Our analysis shows that the most socially beneficial and robust interventions – which have a lower government cost burden and are more beneficial to households in general and also to the poor – are not the same in Nairobi and the Kathmandu Valley. For Nairobi, transitions from charcoal and kerosene to LPG appear most attractive, achieved by using a combined stove subsidy and financing intervention. These conclusions bolster the case for the government's previous policy of a zero-rate value-added tax on LPG to reduce its cost, and its efforts to reduce the supply of charcoal and kerosene and simultaneously to increase access to LPG. A transition to ethanol (from the two aforementioned polluting fuels) also would be beneficial, but the higher costs of this technology and its lower market development makes this transition difficult to implement for the time being.

For Kathmandu Valley, in contrast, social benefits are greatest in transitions to electric induction cooking, especially from LPG, but also from firewood. A stove subsidy plus financing policy intervention is likely to be most effective for fostering this transition, but BCC activities also appear attractive and necessary, due to low public awareness. The potential of electric cooking resonates with the Nepal government's goal of "expanding access to electricity and clean cooking to 100% of the population in five years" (World Bank 2018), but also would require strengthening grid distribution lines and improving substations to cater to growing electricity demand.

In order to accelerate these transitions, both governments should study and evaluate ongoing efforts to ensure that new innovations – such as pay-as-you-go for LPG or new stove subsidy and financing efforts – are effective and reaching the most relevant populations that are current users of polluting fuels. It is also critical to do more work to understand and influence fuel stacking, because urban households often continue to use multiple fuels. Subsidy policies, in particular, would likely be costly and difficult to implement. For electricity, efforts to bolster generation and transmission infrastructure also require careful and thoughtful planning and implementation.

Finally, as these two cases illustrate, different cities have different cooking situations. Context-specific analysis is required to identify the most relevant cooking transitions to pursue, as well as the most attractive policies to foster those transitions. Using the framework developed and presented in these two cases, policy-makers could consider solutions for their own context, including for rural regions, or could examine differences across larger and smaller cities.

Introduction

Globally, nearly 2.8 billion people rely on solid fuels (animal dung, charcoal, crop residue, fuelwood), kerosene and coal for cooking (IEA, IRENA, UNSD, World Bank and WHO 2020). Household air pollution (HAP), resulting from burning these polluting fuels in inefficient stoves, impacts human health, environmental quality and the climate (Anenberg et al. 2013; Lim et al. 2013; Martin et al. 2014; Myhre et al. 2013). The WHO estimates that approximately 4 million premature deaths occur each year due to exposure to HAP (WHO 2018). Unsustainable fuel harvesting of solid fuels also contributes to deforestation and forest degradation (Bailis et al. 2015). Among global regions, Sub-Saharan Africa (SSA) and South Asia (SA) have the highest global shares of polluting fuel users (77% and 61%) and therefore bear a disproportionate burden of HAP impacts (Bonjour et al. 2013). Despite progress in dissemination and uptake of cleaner solutions by an increasing absolute number of people, high population growth in these regions has meanwhile stalled the decline in these shares of solid fuel users (IEA, IRENA, UNSD, World Bank and WHO 2020).

In effect, though various clean cooking interventions are being rolled out and scaled up worldwide, these have not always resulted in significant behavior change or positive impacts (Bailis et al. 2009, Mortimer et al. 2017, Nepal et al. 2011, Rhodes et al. 2014). The literature on the economics of such technologies from the perspective of households and communities suggests that private incentives play an important role in these limited successes: The net benefits from switching to cleaner technology are not always positive for users. Some studies find high annual global net benefits of switching from traditional cooking to improved cookstoves (ICS) (Hutton et al. 2007, Larsen 2014). Others argue for ambiguous but often negative private benefits (Jeuland and Pattanayak 2012; Jeuland, Tan Soo and Shindell 2018); this is in contrast to social benefits which are typically positive and large (Jeuland, Tan Soo and Shindell 2018).[2] In addition, many factors that determine the choice of clean cooking options are difficult to include in cost-benefit analysis owing to their context-specific nature and subjectivity (e.g., tastes, time and risk preferences, perceptions about HAP impacts, and technology aesthetics) (Jeuland et al. 2015, Van der Kroon et al. 2014).

And though global progress towards clean cooking has been more rapid in urban areas, the rising ambient air pollution levels in most major cities in these regions necessitate multipronged mitigation strategies that continue to combat HAP generation as well as address other urban air pollution sources. Previous cost-benefit analysis of clean cooking have primarily been conducted at the regional (Hutton et al. 2007, Larsen 2014) or household levels (Jeuland and Pattanayak 2012; Jeuland, Tan Soo and Shindell 2018), and we are aware of none that have considered the urban context specifically or been carried out at city-level. In addition, no prior analyses have applied a framework based in the economic theory of demand to examine how specific policy interventions (such as subsidies or other incentives) might shift the private net benefits of specific household cooking transitions. Still, this lack of complete analysis has not prevented some from arguing that a household's net benefits calculation will be considerably more

---

[2] This disconnect on its own creates a challenge for policy-making, even if the case for intervention, based on a positive social net benefits argument, is clear. Specifically, instruments are required that would help turn the logic of transitioning positive among private individuals, who will otherwise resist it.

positive in an urban setting than in a rural one. This argument typically rests on a simple assertion that greater scarcity of solid fuels in urban settings, and the fact that most households purchase rather than collect these fuels, render fuel savings particularly salient and valuable for households in these locations (Jeuland, Pattanayak and Peters 2020).

Against this backdrop, we report here results from an urban cost-benefit and policy analysis applied in two contrasting but important settings for studying urban cooking transitions. These cases – in Nairobi and Kathmandu – were selected to provide insights into the differences between these two regions with the greatest persistence of solid fuel use, SSA and SA. While every city is unique, these specific cities do demonstrate important differences across their regions, most notably related to the fuel mix that is typically used by households: Specifically, the widespread use of charcoal in SSA, which is virtually nonexistent in SA. Kerosene use for cooking is also much more prevalent in Nairobi than in Kathmandu. Furthermore, among clean options, though electric cooking is not especially prevalent in either location and liquefied petroleum gas offers the main clean fuel alternative to polluting fuels, policy makers in Kathmandu appear especially interested in the potential for electric cooking, due to the country's high endowment with potential hydropower generation sites.

Focus City in Sub-Saharan Africa: Nairobi, Kenya

Our study focuses on Nairobi as an illustrative urban case in SSA owing to (a) the scale of the air pollution problem in the region (Katoto et al. 2019; Naidja et al. 2018; Schwela 2012), (b) the high use of both charcoal and kerosene in the city (neither of which is considered a clean cooking fuel), and (c) the government's active interest in engendering a clean cooking future. Though the shares of polluting fuel users are somewhat lower in Nairobi (a city's whose sheer size makes it worthy of attention), Kenyans in urban areas overall (27.8% of the total population) exhibit primary reliance on several fuels: LPG (46%), firewood (21%), charcoal (17%) and kerosene (16%) (CCAK and Kenya MoE 2019; Worldometers 2018).

Kenya is also an important country for studying problems related to polluting fuels. Over 80% of Kenya's population still relies primarily on wood and charcoal stoves for cooking (CCAK and Kenya MoE 2019), despite Kenya being an early leader in East Africa in establishing a market for improved cookstoves (ICS) such as the Kenyan Ceramic Jiko (KCJ) in the 1980s (Accenture Development Partnerships 2012). The government and private sector have continued to push ICS and clean fuels, in part to meet the country's emissions reduction targets under the Paris Climate Agreement. Specific policy interventions include a voluntary and sector-driven labeling program for clean cooking technologies that is currently under development, and removal of the value added tax (VAT) on liquefied petroleum gas (LPG) (Clean Cooking Alliance 2018).[3] Nationwide, estimates suggest that 22,109 deaths annually can be attributed to polluting household fuel use (Global Burden of Disease Collaborative Network 2020). Solid fuel use is meanwhile considered a key contributor to declining forest cover, which stood at 6.9% in 2017 (Government of Kenya 2018). Finally, though Kenya has strict air quality regulation standards, monitoring of pollution sources is

---

[3] However, a recent media article reports that the International Monetary Fund (IMF) is pressuring the Government of Kenya to raise prices of LPG and other basic goods like bread, and maize and wheat flour by at least 16% (Business Daily, 2020). Stakeholders are in the process of submitting petitions to reject this proposal.

quite limited, including for particulate matter; for example, we were unable to find systematic, publicly available measures of pollution levels in Nairobi, East Africa's largest city.

Focus City in South Asia: Kathmandu, Nepal

Kathmandu faces severe air quality challenges. The entire valley is very dense and the city is considered one of the most polluted in Asia, with daily average $PM_{2.5}$ concentrations between 30 to 207 μg m−3, far exceeding the WHO 24-hour guideline by factors of 1.2 to 8.3 (Islam et al. 2019). This urban metropolis is experiencing rapid urbanization, and pollution sources are diverse, arising from construction, poorly regulated industrial activity, open burning of solid waste, and household burning of firewood (Parajuly 2016). Specific to outdoor $PM_{2.5}$ in Kathmandu Valley, Islam et al. (2019) find that household sources, namely continuing biomass and garbage burning, are major contributors to ambient air quality problems. And though the proportion of solid fuel users for cooking is fairly low in Kathmandu, at only 12%, similar to Nairobi, this nonetheless represents a significant proportion of the urban population nationwide. Given that more than 25% of urban dwellers nationwide (who comprise 44% of the country's total population) use solid fuels for cooking (Government of Nepal 2012), this population is relevant to considering the urban fuel transition in this country overall.

As a country, Nepal faces numerous environmental challenges, which manifest in substantial health and economic costs. The Environmental Performance Index places Nepal last out of 180 countries on air quality, as measured by indicators of household solid fuel use, $PM_{2.5}$ exposure and exceedance measures (Yale University 2018). Approximately 80% of Nepal's total population relies on solid fuels (mainly firewood and animal dung) for cooking. Nationwide, the number of deaths attributed to HAP is estimated to be 21,603, with 2,048 of these among children under 15 years old (IHME, 2020). The Terai and Siwaliks regions have also experienced rapid deforestation owing to conversion of forest to agricultural land and increased infrastructure development (DFRS, 2014a, 2014b).

Against this backdrop, a recent major transition in governance provides new opportunities for policy interventions and environmental protection. National plans and legislation to address these challenges include efforts to spur development and introduction of efficient ICS; promotion of cleaner fuel and technology; and strategies for ambient urban air quality management, such as promotion of environmentally sustainable transportation (Saud and Paudel 2018). The government's commitment to significantly increase electricity production using the country's abundant hydro resources and related interest in promoting electric cooking (Pakhtigian et al. 2019; Wu et al. 2013), make urban Nepal an interesting case study for two additional reasons. The first relates to assessing the potential for an energy security-enhancing transition from one clean fuel (LPG) to another (electricity) in the capital city of a low-income country—a rarity among countries with high HAP levels. Second, the production of electricity using renewables and subsequent policy directives encouraging households to switch to electric cooking will enable Nepal to achieve multiple Sustainable Development Goals: Numbers 3 (Good Health and Well-being), 7 (Affordable and Clean Energy), 11 (Sustainable Cities and Communities) and 13 (Climate Action).

Why this report focuses on costs and benefits in the urban context

As noted above, the majority of the population in low- and middle-income countries relying on biomass and other polluting fuels resides in rural areas. Yet the transition to clean cooking remains a challenge in most peri-urban areas and informal settlements in developing country cities (WHO 2018). In Central America, for example, income growth is projected to enable urban households to fully switch to modern cooking energy services only by 2030 (Pachauri et al. 2018). In Nairobi, there is continued reliance by considerable shares of the population on kerosene – a fuel that the WHO recently classified as a polluting fuel (30%) – and charcoal (6%) (CCAK and Kenya MoE 2019). Consistent with global trends, the Kathmandu Valley region already has substantial LPG use as a primary cooking fuel (84%), but primary firewood users still comprise about 11% of the population (Government of Nepal 2012). In SA overall, in 2010, $PM_{2.5}$ from HAP contributed to 26% of ambient $PM_{2.5}$ (Chafe et al. 2014). The contribution of HAP to ambient $PM_{2.5}$ from domestic fuel burning in urban SA is estimated to be approximately 13%,[4] and reaches 34% in urban SSA (Karagulian et al. 2015).[5] Recently, Mahapatra et al. (2019) found that background pollution contributes to 20-25% of local pollution (as measured by aerosol optical depths) in the Kathmandu Valley.

The sparse literature on energy use in cities in SSA has focused mainly on energy use efficiencies (Anozie et al. 2007), particulate pollution (Antonel and Chowdhury 2013; Mkoma et al. 2013; Van Vliet and Kinney 2007; Zhou et al. 2013), source apportionment (Gaita et al. 2014), and ISO technology standards (Nerini, Ray and Boulkaid 2017), without adequately considering economic and social science aspects of the problem. The few such studies conducted in urban Kenya are on energy consumption patterns (Hughes-Cromwick 1985; Karakezi, Kimani and Onguru 2008; Ngui et al. 2011) and fuel choices (Treiber et al. 2015). Air pollution research in the Kathmandu Valley has similarly largely focused on emissions from outdoor sources (Kim et al. 2015), and on health impacts (Gurung and Bell 2012; Melsom et al. 2001). This complements broader evidence from Nepal linking biomass fuel use with the prevalence of respiratory infections (Shrestha and Shrestha 2005) and tuberculosis (Pokharel et al. 2010). Studies conducted in rural Nepal have also considered ventilation and clean fuels, and have obtained varying results for impacts on health: some find negative associations between kitchen ventilation and the prevalence of cataracts (Pokharel 2005); others find that use of clean fuels like biogas reduces prevalence of chronic bronchitis and acute respiratory infections (Pant 2007). Pant (2012) finds use of dung briquettes to be associated with increased prevalence of asthma and eye diseases. Bates et al. (2019) find surprising positive associations between LPG use and cases of pulmonary tuberculosis, likely due to inadequate control for confounding or selection into LPG use.

---

[4] Karagulian et al. 2015 include Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan and Sri Lanka under the Southern Asia group. Source apportionment was calculated separately for India.

[5] We use these source apportionment figures from Karagulian et al. 2015 in our analysis for Nairobi and Kathmandu. Karagulian et al. 2015 include the following countries in Africa: Algeria, Angola, Benin, Botswana, Burundi, Burkina Faso, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Côte D'Ivoire, Djibouti, Egypt, Ethiopia, Equatorial Guinea, Eritrea, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Lesotho, Liberia, Libya, Kenya, Madagascar, Malawi, Mali, Mauritius, Mauritania, Morocco, Mozambique, Namibia, Niger, Nigeria, Republic of Congo, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Sudan, South Africa, Sudan, Swaziland, Tanzania, Togo, Tunisia , Uganda, Western Sahara , Zambia, Zimbabwe.

This health evidence notwithstanding, policy-makers especially need information on the rationale for policies that would shift consumers of polluting fuels to use of cleaner options. Alternative policies have dramatically different cost implications, which affect both the ability of resource-constrained governments to intervene and scale interventions, and the speed of transitions and therefore overall welfare benefits delivered. Though Malla et al. (2011) conducted cost-benefit analysis of specific stove interventions in peri-urban and rural Kenya, and in rural Nepal, their calculations were incomplete: They considered a set of technology-based interventions that lacked policy detail. A few limited studies of the health costs and benefits of using clean cooking technologies in Nepal (Pant 2007; Pant 2012) have neither included the full suite of costs and benefits nor calculated net benefits. At a global level, there is overwhelming focus on emissions and health impacts (Jeuland et al. 2020), but very limited understanding of the practice and benefits implications of policy instruments meant to stimulate clean cooking energy use in the urban centers of developing countries (EnDev 2012).

Our approach

In this report, we extend an existing rigorous framework to allow for such analysis in the context (Jeuland, Tan Soo & Shindell, 2018). In each of our policy sites (Nairobi and Kathmandu), we first outline baseline conditions, and discuss the hypothetical health, well-being, environment and climate implications of fully transitioning to several potential cleaner cooking solutions. It is important to note that these initial calculations of potentials are hypothetical because real-world interventions have rarely succeeded in inducing a complete, immediate shift to clean solutions (Jeuland et al. 2018). Thus, in the subsequent policy analysis for each location, we shift to a description of the net benefits (social and private) of each household cooking transition under five real-world policy interventions given the limited evidence on the effectiveness of such strategies. The interventions include a stove subsidy alone, a combined stove and fuel subsidy, a combined stove subsidy and financing intervention, a combined stove subsidy and behavior change communication (BCC) campaign, and lastly, a polluting fuel ban. Our results are meant to inform policy-makers about the relative merits of these different strategies for accelerating clean cooking transitions, but readers should be cognizant that our predictions rest on a thin evidence base and that it thus remains essential to continue to generate high quality evidence on policy effectiveness in this domain.

Background

This section describes current energy-related policies that are planned or being implemented in Kenya and Nepal. These policies were identified from a document review facilitated by the Clean Cooking Alliance (CCA) and its country offices in Kenya and Nepal, and from a series of meetings and discussions held in Nairobi in October 2018 and Kathmandu in March 2019. Based on these qualitative interviews and consultative meetings, we also provide perspectives from select stove manufacturers and non-profit organizations, particularly concerning their response to the clean cooking policy dynamics and environment in their respective countries.

Focus City in Sub-Saharan Africa: Nairobi, Kenya

Strategies and policies on clean energy and clean cooking

The Kenyan Government's Energy Act 2019 mandates that each county government develop and submit its own energy plan (Government of Kenya 2019). Under this law, the Energy and Petroleum Regulatory Authority (EPRA), along with the Kenya Bureau of Standards (KEBS), is responsible for ensuring that only energy-efficient and cost-effective appliances and equipment are imported into Kenya (Government of Kenya 2017).[6] The Rural Electrification and Renewable Energy Corporation, among other roles, was created to "develop and promote in collaboration with other agencies, the use of renewable energy and technologies, including but not limited to biomass, biodiesel, bio-ethanol, charcoal, fuelwood, solar, wind, tidal waves, small hydropower, biogas, co-generation and municipal waste, but excluding geothermal" (Government of Kenya 2017). The provision of an enabling framework for the "efficient and sustainable production, conversion, distribution, marketing and utilization of biomass, solar, wind, small hydros, municipal wastes" also rests with this corporation. Finally, the law established a Renewable Energy Resource Advisory Committee and a renewable energy feed-in-tariff system to speed up electricity generation through renewable energy sources.

Kenya has an ambitious goal of universal electricity access (grid extension along with off-grid technologies, mini grids and independent solar systems) by 2022 (World Bank 2018), while 2028 is the target year for achieving modern cooking services to all Kenyan households (CCA 2019).[7] The regulation of the fuelwood sector with a draft Forest Act along with a six-point system of control from producer to consumer is being envisaged. However, the Forest (Charcoal) Regulations 2009 have yet to be fully adopted.[8] Four priority areas outlined in a Country Action Plan, currently under review, include (i) improving the policy and regulation of the energy sector, especially for charcoal production, appropriate

---

[6] Figure B1 shows the different stakeholders in the clean energy and clean cooking sector in Kenya. Appendix B1 describes the role of each of these stakeholders in more detail.

[7] Only 23% (about 1.97 million households) of the Kenyan population, had grid electricity supply in 2013. Access to modern cooking services was at 3.2 million households, according to market assessment of Clean Cookstoves Association of Kenya (CCAK) under the Kenya Country Action Plan 2013 (KCAP). Over 80% of Kenyans thus relied on the traditional use of biomass as the primary source of energy for cooking and heating with firewood contributing 68.7% and charcoal 13.3%." (SE4All Action Agenda Report for Kenya, 2018).

[8] Details of the Forest (Charcoal) Regulations 2009 are in the Background section ("Policies related to specific cooking fuels and stoves").

forestry management plans and afforestation efforts; (ii) building human and institutional capacity; (iii) increasing access to electricity; and (iv) increasing access to modern cooking solutions, including a cross-sectoral initiative to bring together various ongoing efforts and improve coordination across agencies, the private sector, community service organizations and NGOs (SE4All Kenya Action Agenda 2016).

The Ministry of Energy (MoE) is at the forefront of (i) awareness creation of the numerous benefits of ICS and clean fuels (along with CCA, GIZ, Practical Action and SNV among other key stakeholders); (ii) implementation and development of cookstoves dissemination projects; and (iii) definition and scale-up of certification processes for residential and commercial cookstoves (SE4All Kenya Action Agenda 2016). Along with partner organizations, the Kenyan government has developed standards for both biomass and charcoal stoves (focused on efficiency, $PM_{2.5}$ and CO emissions, durability and safety) that need to be enforced.[9] While government programs thus far have emphasized provision of electricity over clean cooking, the MoE now has a World Bank-funded five-year program, the Kenya Offgrid Solar Program (KOSAP), whose second component is currently under implementation and combines off-grid electricity with clean cooking, in addition to promoting stand-alone solar home systems (World Bank 2020).

The Clean Cooking Association of Kenya (CCAK) – a local association of all actors in the clean cooking sector, that primarily plays a financing role – and the Ministry of Health (MoH) through its Climate Change, Energy and Health Technical Working Groups, have developed draft manuals and curriculum for training of community health volunteers and extension workers. As of October 2018, the MoH was undertaking field testing of these manuals to facilitate their finalization and launch. The overall goal of this effort is to educate households about the link between HAP and development outcomes, and on how to mitigate negative HAP impacts. The Ministry has included HAP in its universal coverage policy between 2018-2022, that seeks to ensure that all have access to quality and affordable health. With support from CCA, the MoH has also received low-cost equipment to measure air pollution in households, to support continuous monitoring of air quality and assessments of the link between HAP and maternal and child health. As of 2017, Kenya had no robust system or standardized structures for monitoring air quality and subsequent reporting and dissemination, however (Kenya Air Quality Management Sub-Committee Report 2017). In early 2017, a National Committee on Air Quality Management and Coordination recommended establishment of 15 new air monitoring stations in big cities including Nairobi, Mombasa, Kisumu and Nakuru to address this lacuna (Kenya Air Quality Management Sub-Committee Report 2017).

Under Kenya's National Climate Change Action Plan (2018-2022), led by the Ministry of Environment and Forestry (MoEF), there is prioritization of electricity supply from renewable sources and encouragement of clean cooking transitions. Concerning the latter, the Plan specifies a goal of increasing the number of a) urban households using LPG, ethanol and other clean fuels to 2 million, and b) rural households using improved biomass (charcoal and wood) cookstoves to 4 million (Government of Kenya 2018), by the end

---

[9] The following standards now exist: (1) Kenya Standard- Biomass stoves- performance requirements, Fourth edition. This standard replaced the KS 1814:2018 Kenya Standard- Biomass stoves (revised); (2) Kenya Standard- Meter for dispensing Liquefied Petroleum Gas (LPG) from cylinder- Specification, First edition (new); (3) Kenya Standard- Clean cookstoves and clean cooking solutions-Harmonized laboratory test protocols Part 1: Standard test sequence for emissions and performance, safety and durability, First edition.

of June 2023. As per the latest estimates (CCAK and MoE 2019), 64.7% of Kenyan households (8.1 million) use wood as their primary fuel for cooking, 19% primarily use LPG (2.4 million) and 10% primarily use charcoal, for cooking purposes (1.3 million). In addition, 14% of Kenyans, and 28% in urban areas, rely primarily on kerosene for cooking. Importantly, many households stack fuels: the prevalence of woodstove use – either as a primary or secondary stove – is substantial at 92%. And though LPG use increased six fold between 1999-2018 from close to 0.6 million to 3.7 million (54% in urban and 18% in rural locations), primary LPG users continue to stack polluting fuels: Among primary LPG users, the amount of charcoal used, for example, on average is 42% of that used by households that primarily rely on charcoal for cooking.

Policies related to specific cooking fuels and stoves

Charcoal

Approximately 17% of Kenya's urban population and 7% of its rural population relies on charcoal for domestic energy (CCAK and MoE 2019). Though the charcoal industry is the largest contributor to job creation relative to other sectors (Government of Kenya 2018), the informal nature of the sector and non-industrial production of charcoal renders regulation and management of its production and supply a challenge. Along with the MoEF, MoE is attempting to promote briquettes from coffee and coconut husks, and sugar waste (bagasse) to reduce pressures on forests. Standards for the production of sustainable charcoal and carbonized briquettes are under development. While charcoal-burning kilns are being promoted, there are no production or labeling standards for artisanal charcoal stove production (e.g., there are no standardized procedures or guidelines for replication of the Cookswell Jiko manufactured Kenya Ceramic Jiko, also known as the KCJ).

According to the Forest (Charcoal) Regulations 2009, the Kenya Forest Service is the only authorized entity for issuance of licenses for charcoal production and transport. These regulations mandate several things. First, that all commercial charcoal producers be organized to form charcoal producer associations that encourage sustainable charcoal production (with the underlying goal of making licenses affordable). Second, licensing committees formed under forest conservation committees review applications for charcoal producer licenses (paying special attention to places of intended charcoal production, designated charcoal collection centers, consent of individuals on whose land charcoal is produced, type of tree species, and estimated volume of trees to be harvested) and approve proposed charcoal production plans. Third, land owners intending to produce charcoal for self-consumption do not need a license but land owners intending commercial charcoal production do. And fourth, charcoal or charcoal products can be moved from one location to another only if the person is in possession of a valid charcoal movement permit, has a certificate of origin for charcoal, and has an original receipt from the vendor (Government of Kenya 2009).

On February 26, 2018, the Cabinet Secretary for Environment and Forestry issued a gazette notice appointing a Taskforce for 30 days to examine forest resources management and logging activities in Kenya. Specifically, for charcoal, the notice stated that the Taskforce would "review the statutory and regulatory regime governing charcoal burning and trade, and make recommendations on the need, or otherwise, to ban charcoal burning, trade or use." (The Kenya Gazette 2018). Government officials across ministries maintain that since the charcoal industry is a large employer, particularly in the informal sector, a ban is not an appropriate solution and that sustainable forest management is of more critical concern.

In its report, the Taskforce recommended development of sustainable charcoal production and management standards, and “aggressive promotion and scale-up of already researched alternative energy sources to increase accessibility and availability of these alternatives” (Government of Kenya 2018). Importantly, the maximum fine on “making and possessing charcoal in a national, county or provisional forest; or in a community forest, private forest or farmlands without a license or permit of the owner” is 50,000 KES or a maximum imprisonment term of 6 months (Government of Kenya 2018).[10]

While there is ambiguity among charcoal producers and buyers of how and when these recommendations will come into effect, charcoal is available widely in local markets albeit at double the price compared to that in the months prior to issuance of the gazette notice. Charcoal is now more expensive to use than LPG. Donor agencies argued for regulating the charcoal transport sector by providing them licenses and permits, establishing government schemes for plantations specifically for charcoal production, and incentivizing small-scale pellet and briquette entrepreneurs.[11]

Biomass-fuel Improved Cookstoves (ICS)

In the 1980s, ICS programs were designed to give households free ICS. However, some have argued that partial contribution to these technologies is needed to encourage households to better use them (Rehfeuss et al. 2013), despite some contrary evidence in the broader literature, i.e., that free stove provision does not spoil demand or reliance on effective and user-friendly technologies (Bensch and Peters 2015, Bensch and Peters 2020). In the current ICS landscape in Kenya, the VAT has been reinstated as of June 2020 (The Star 2020). This affects companies that import stoves (such as BioLite, which also now owns EcoZoom), however owing to reduced import duties on ICS parts, companies such as Envirofit that import parts but assemble stoves in-country remain unaffected. The Kenya Association of Manufacturers (KAM) and the Ministry of Industry, Trade and Cooperatives petitioned for import taxes to be increased to encourage local manufacturing and employment. As the only in-country stove manufacturer, Burn Manufacturing, which produces the popular Jikokoa ICS, has benefitted from this move. In addition, the unfavorable tax regime is not conducive to budding entrepreneurs in the sector. This includes payment of a 15% presumptive tax on the value of an annual trading license for companies with turnover less than 5 million KES in a year of income, and that are issued or liable to be issued with a business permit or trade license (Kenya Revenue Authority 2020); an additional Turnover Tax (TOT) of 3% on the gross sales or turnover for companies/businesses with turnover less than 5 million KES in a year of income and not VAT-registered (Kenya Revenue Authority 2020); and high electricity tariffs.

As the Kenyan government is keen on a market-driven approach for ICS, no government subsidies are given for these technologies. Donors and development organizations, however, may subsidize ICS for their beneficiaries. While the MoE sees value in combining clean cooking programs with other related social programs, it has no existing plans to engage in developing complementary policies.

---

[10] 1 USD=99.4271 KES (as of December 22, 2019). Source: https://www.oanda.com/currency/converter/

[11] The United Briquette Producers Association-Kenya, formally registered in 2019, comprises government representatives, those from the private sector, NGOs, academia, donor agencies, and others working in the carbonized briquette sector.

Kerosene

In Kenya, until early 2018, there were no government directives discouraging kerosene use owing to low awareness of the harmful links between kerosene use and negative health effects. Since then, punitive pricing policies are increasingly being leveraged to discourage use. Apart from being a polluting fuel, owing to its low prices, kerosene had historically been used to adulterate diesel, which led to market distortion and increased failure of machinery. The Petroleum Institute of East Africa (PIEA) proposed that kerosene be made unprofitable by increasing the excise duty on that fuel. The revenue generated from increased kerosene prices could then be used to support LPG procurement and subsidize the cost of LPG cylinders. As of October 2018, kerosene is priced on par with diesel. Along with PIEA, CCAK and EPRA lobbied for an increase in kerosene price and a reduction in the price of LPG. Some bureaucrats in various ministries acknowledge that while the kerosene tax has led to doubling of prices, alternate sources of cooking energy are not yet affordable to many.

Ethanol

In East Africa, ethanol is a by-product of the existing sugar refining process (i.e. it is molasses-based). Though ethanol is in its nascent stages of production and extensive distribution in Kenya, it holds promise as a clean fuel alternative, especially for urban populations, as kerosene prices soar. Since ethanol stoves are currently priced higher than charcoal ICS and the fuel is not widely available, their penetration among low-income households remains low. While some small-scale enterprises distribute ethanol, such as Consumer Choice and Leocome, KOKO Networks, which obtains imported ethanol from the upstream distributor Vivo Energy, is the major private sector ethanol promoter.[12] In distinguishing it from alcohol, ethanol for cooking is denatured at the source. Given the few ethanol providers currently in the Kenyan market, widespread availability, cost and reliability of ethanol supply remain important supply-side challenges.

LPG

The government's LPG policy prior to 2016 lacked policy specificity, details on implementation, and moreover did not set clear mandates, but rather made broad statements about protecting the environment. A new policy, developed in a technical committee organized in 2016 (where PIEA was an active participant), has clear statements related to the goal of converting users of competing fuels and kerosene to LPG by 2020 (first timeline) and 2030 (final timeline). It specifies how 100% conversion can be achieved, and highlights the major challenges to meeting this goal, which include (a) cost, (b) access, (c) awareness & sensitization, (d) lack of knowledge concerning the relationship between LPG use and health and environmental degradation, and (e) an ingrained reliance on charcoal and firewood.

As a lobbying body that supports government policy and guides the private sector on investment, PIEA's involvement with the MoE ensured systematic policy directives on LPG with action plans. Among the infrastructure deficiencies that PIEA outlined were storage, cylinder filling, and cylinder supply. PIEA

---

[12] As of September 15, 2020, KOKO Networks had sold 50,000 cooker kits in Nairobi (Disrupt Africa 2020). Their innovative "V2.0 Smart ATM Network" approach to bioethanol cooking fuel lowers the retail price of ethanol by approximately 45%, compared to a traditional centralized bottling model (Stakeholder Interviews, 2019 and Email communication with KOKO Networks, 2020). The latter model is typically expensive, owing to additional costs of bottling facilities, packaging and last-mile retailer margins (KOKO Networks 2018).

pushed for LPG to be zero-rated (0% import duty)[13] and for kerosene and charcoal supply to be minimized in the market. The existing regulatory framework which was not consumer safety-friendly was amended. According to the Petroleum (Liquefied Petroleum Gas) Regulations of 2019 (Legal Notice No. 100), cylinder exchange from rival oil marketers is disallowed to protect consumer safety and provide an ownership guarantee (EPRA 2019).

PIEA has been lobbying aggressively for the past 4 years and received support from the MoE, Ministry of Petroleum & Mining, and EPRA, to have the National Treasury equalize taxes on kerosene and diesel (also known as the anti-adulteration levy). Between November 7, 2019 to June 30, 2020, the value-added tax on LPG was zero-rated (RSM International Association 2019), with the intention of making LPG an accessible and affordable clean fuel. However, since June 30, 2020 the 14% VAT has been reinstated (Ernst and Young 2020). While LPG supply is not regulated, the government plans to standardize procurement of LPG – similar to kerosene and petroleum.

Technological innovations are also facilitating LPG provision and financing opportunities for first-time LPG users, particularly in informal urban settlements. Pay-as-you-go[14] technology (e.g., Pay Go; Envirofit's model), piloted in some informal settlements in Nairobi, allows consumers to buy LPG in smaller quantities (to ease liquidity constraints or transport challenges); it connects consumers to retailers, retailers to distributors, and the latter to suppliers. Entirely based on the M-PESA technology (which Kenyans are already using for solar energy and electricity), LPG top-up depends on consumers' need, and is largely targeted at daily wage workers who previously could not afford LPG.

Following the establishment of the Petroleum (Liquefied Petroleum Gas) Regulations of 2019, PIEA also conducted sensitization workshops among LPG stakeholders (storage owners, distributors, retailers, cylinder manufacturers, validators) on the new policy's features. Unlike previous policies, the new one is not limited to consumers, but also includes regulatory agencies and all stakeholders along the value chain. For existing and potential LPG consumers, PIEA has been using conventional and non-conventional media, through content-based packaging or dissemination via social media and dedicated articles in the press, to emphasize LPG's accessibility, affordability, and long-term welfare gains (e.g., children's education, income generation/expansion, health, environment).

---

[13] More information on the distinction between zero rating and VAT exemption is provided here: https://www.taxpolicycenter.org/briefing-book/what-difference-between-zero-rating-and-exempting-good-vat [Accessed: June 9, 2020]

[14] In the LPG Pay-Go Model, the cylinder is connected to a meter that reflects fuel quantity and signals refilling. Refilling say 100 KES worth of LPG could be done through one's mobile phone (Pay-Go application). That information goes to the Pay-Go's back office that in turn does a run for households where cylinders need to be replaced. If there is LPG remaining in a cylinder at the time of exchange, Pay-Go will credit the household the equivalent of LPG's worth and debit for whatever is increased in the cylinder i.e. household only pays for the additional LPG. Such a system's advantage is the asset control: brand owners are guaranteed that the asset is being utilized, they are the ones filling cylinders; that they are taken back to the same facility for repair, and likewise for refilling. There is also a connection now between distributors and retailers, where the latter informs the former of what is required in a certain location and time frame. Since the retailer and consumer are connected, the retailer is always aware of consumers' needs.

The response of stove manufacturers and distributors to clean cooking policies

The government's Big Four Agenda (2018) includes ensuring food security, providing affordable housing, increasing manufacturing, and making healthcare affordable. Some international stove manufacturers and distributors benefit from the government's local manufacturing policy agenda by virtue of their business model (e.g., Burn Manufacturing). However, in the absence of an established market for ICS, other international companies (e.g., EcoZoom, BioLite) refrain from making manufacturing investments in the country and continue to operate on thin distribution margins. Locally-made products can be standardized to meet the KEBS benchmark but local stove companies (e.g., Cookswell Jiko) do not benefit from these investment-driven policies as they have limited capital. It is unclear if the East African Community Common External Tariff (CET) reduction on import duty for ICS from 35% to 25% (for the fiscal year 2019-2020) has been able to attract any new players into the market.

In keeping with LPG policy reforms and the changing clean cooking market, Envirofit is piloting an LPG-pay-as-you-cook technology among 1,200 households in low- and middle-income neighborhoods in Nairobi. Households are given a 13.5kg gas cylinder and two-plate cooker, if they do not already own one. Atop the cylinder is a smart meter, and households can buy refills for as little as 50 cents worth of LPG through M-PESA.

The development sector's response to clean cooking policies

Insights in this section are drawn from interviews conducted in October 2018 with select development organizations that were available for interviews. It is important to note that progress in the clean cooking sector in Kenya is the result of collective coordination from various development organizations, and not necessarily the limited set discussed below.

Though SNV has traditionally been involved in biogas programs in rural Kenya, they have now expanded to ICS and are moving towards LPG promotion. The organization is considering supporting a pilot ethanol market in the Kakuma refugee camp. SNV's clean cooking program is a results-based financing (RBF) program funded through EnDev (GIZ), and SNV is also one of the facility managers for KOSAP Component 2, described previously. In an RBF scheme, development agencies enter into contracts with stove manufacturers, distributors and retailers for market penetration of their Kenya Industrial Research and Development Institute (KIRDI)-tested stoves. The RBF incentives to partner organizations vary by ICS categories or tiers (i.e. for each stove a company/organization sells, EnDev provides certain incentives). SNV is also among the few organizations conducting a study on institutional cooking in schools and prisons using clean cooking technologies; the program includes establishment of technology standards.

GIZ Energy is primarily focused on improved cooking technologies and lighting in rural Kenya, but its program offers important insights for urban settings. It aims to understand the supply for and quality of ICS, the need for a consumer-oriented approach and education, and the design of appropriate marketing and promotion strategies around ICS.

Equity Foundation's (the corporate social responsibility division of the Equity Bank Group) EcoMoto Loan enables customers to access clean cooking and lighting solutions conveniently and under attractive financing conditions.[15] What started as a paper loan process with minimal uptake is now available in a mobile phone application that reaches many more beneficiaries. The Foundation focuses on (i) developing loans, (ii) creating distributional networks [currently Equity Bank has 177 branches and over 35,000 agents; some agents (~20-30 per branch) can also become distributors of clean cooking technology]; and (iii) selecting ICS products (there are currently three partner companies: BioLite, Burn Manufacturing, and Envirofit).

Responding to Kenya's transition to LPG and changing LPG policy reforms, Equity Foundation is also promoting Proto Energy's LPG cylinders, which are manufactured in-country and distributed through agents in urban Kenya. For rural Kenya, Equity Foundation is partnering with the National Oil and Global LPG Partnership on a pilot initiative through which households can obtain a loan of less than $100 (i.e. 9,990 KES) for a 13kg LPG cylinder, hose pipe and 2-burner stove. For subsequent refills, beneficiaries can borrow 750 KES and pay this back over time in small installments. Equity Foundation uses a group lending channel, where a group comprises about 30 women, each taking a loan for different purposes (e.g., purchasing cows, iron sheets, ICS). It also creates educational messages that are disseminated through radio, fliers, seminars, road shows and cooking competitions. While other financial institutions exist (e.g., micro-finance institutions with ~10,000 members and savings and credit cooperatives with about 5,000 members), Equity Foundation's strength lies in its very large customer base of over 12.5 million.

In the domain of information, education and communication (IEC) and BCC, Population Services Kenya (PSK) has been working on clean cookstoves for about 2 years, initially with support from the Clean Cooking Alliance for the "Upishi Digi" campaign.[16] Their approach involves a strategy of segmenting messages by target groups (one for charcoal ICS and another for cleaner options such as biogas, ethanol, LPG and electricity), working to solve demand side issues related to access to and infrastructure for products, creating financing options for cash-constrained households, and engaging other sources for message dissemination such as community health volunteers. GIZ is currently supporting PSK's last mile approach of engaging community health volunteers in three counties.

The United Nations Environment Program (UNEP), though not an active player in the clean cooking domain, has three foci that relate to this problem. The first is affordable monitoring of air quality, supplementing existing infrastructure and identifying areas of high pollution (hotspots). Currently, there are six monitoring units around the city and identified hotspots include a mix of sites (e.g., highway, industrial sites, and urban background sites with high informal settlement density). Second, UNEP supports countries in their efforts to develop air quality policies. Based on evidence from the first pillar, air quality action plans are developed. Third, public awareness programs such as "Breathe Life" are developed with partner organizations like the WHO and Clean Air Quality, to showcase best practices and allow for cross pollination of ideas from different agencies and international organizations.

---

[15] Specifically, interest of 13% per annum is charged on a declining balance, and 6.5% for a balance less than 5,000 KES.

[16] PSK has been a locally registered, independent Kenyan entity since 2014, when PSI's Kenya operations underwent a transition. PSK works closely with private sector stakeholders, ranging from large commercial distributors to small kiosks, to support a network of more than 320 private providers at Tunza franchised clinics and community-based organizations, as well as many other institutions, suppliers and partners.

Focus City in South Asia: Kathmandu, Nepal

Strategies and policies on clean energy and clean cooking

In May 2018, the Nepal government released the White Paper on Energy, Water Resources and Irrigation Sector's Status and Roadmap for the future (hereafter "the White Paper"), that identified energy and water resources as being central to achieving sustainable development in Nepal (World Bank 2018). The government also declared the 2018-2028 period the 'energy and water resources decade'. This white paper is largely devoted to electricity goals: "(a) To reach 5,000 MW installed capacity in 5 years and 15,000 MW installed capacity in 10 years, (b) To expand access to electricity and clean cooking to 100% of the population in 5 years, and (c) To increase the per capita consumption of electricity to 1,500 kWh in 10 years" (World Bank 2018). The government also "plans to initiate an 'electric stove in every household program'" (Government of Nepal 2018). To achieve its goal of universal electric cooking access, the Government of Nepal "plans to increase electricity generation through the installation of 5,000 MW of hydropower in five years and 15,000 MW in fifteen years" (ibid).

To support these goals, the document mentions five specific actions. First, development of a master plan for electricity distribution for each province by 2019. Second, the launch of a national-level campaign in close coordination between federal, provincial and local levels of government, to increase electricity access for all by 2022. Third, establishment of renewable battery storage systems (using solar, micro hydro and wind sources) in locations where grid connections are infeasible. Fourth, strengthening of distribution lines and improvement of substations to cater to growing electricity demand in Kathmandu Valley and Pokhara, with potential laying of underground electric distribution lines where feasible and based on safety or environmental considerations. Finally, development of policies to encourage use of electric vehicles, including installation of charging stations (Stakeholder Interviews 2019).[17]

Furthermore, the Nepal government has been keen to reduce LPG import and increase energy independence since the trade blockade (with India) of 2015. Policy makers recognize the unsustainability of LPG import in the long-run and the foreign exchange problems it entails, and have ambitions to leverage the country's significant hydropower potential. The white paper mentions establishment of a program to disseminate an "Electric Stove in Every House" to decrease HAP and reduce reliance on LPG imports.

The government's earlier clean cooking initiatives were focused on biomass or biogas solutions. Biogas programs in particular have been promoted in rural Nepal since the late 1970s, and as of 2016 the government provided subsidies ranging between 16,000 and 35,000 NPR for new installations, depending on the size of plant (2 cubic meters, 4 cubic meters or 6 cubic meters and above) and region, i.e. Terai, Hill or Mountain (Government of Nepal 2016).[18] Nepal's Biomass Energy Strategy (BEST) 2017 aims to achieve a HAP-free Nepal by 2022. The goal is to promote clean cooking technologies in all households

---

[17] Ms. Karuna Bajracharya, Country Manager- Nepal at Clean Cooking Alliance translated this section of the White Paper from Nepali to English.

[18] 1 USD=108.43 NPR [Accessed: July 6, 2019]. Source: https://www1.oanda.com/currency/converter/

and ensure the availability of at least Tier-III level ICS in all households currently using biomass fuels, by 2030.

Recently, in an important policy shift, attention has turned towards electric cooking powered by renewables. The 15th Five-Year Plan for example describes the government's aim to increase electricity generation as well as consumption, particularly in urban areas and gradually in peri-urban and rural areas (Government of Nepal 2019; Stakeholder Interviews 2019).

The Alternative Energy Promotion Center (AEPC), currently under the Ministry of Energy, Water Resources and Irrigation, is the focal agency for off-grid electricity and clean cooking solutions in Nepal. Using robust community guidelines, it promotes two main types of clean household energy technologies to encourage the transition away from polluting fuels: metallic and rocket ICS. Given that local governments, under the federal system, are in-charge of clean cooking, AEPC plays a facilitating role on use of the federal government-allocated renewable energy budget and on how best to coordinate renewable energy promotion efforts.

Meanwhile, the National Oil Corporation (NOC), under the Ministry of Commerce and Supply, is responsible for petroleum and LPG supply. It has a total of 54 bottling plants across Nepal, and approximately 30 LPG bottling companies operate in Kathmandu Valley alone. The NOC collaborates with private companies to promote LPG use, and manage risk and safety, but does not engage in direct promotion of clean cooking among end users. The Nepal Electricity Authority (NEA) is the state-owned enterprise responsible for grid electricity provision, and aims to achieve a supply that is adequate, reliable and affordable, through planning, construction, operation and maintenance of generation, transmission and distribution facilities across Nepal's power systems. The newly formed Electricity Regulatory Commission (ERC) is mandated to "oversee power generation, transmission, distribution and trade" (Kathmandu Post 2019).

A common theme that emerged during stakeholder interviews was that inter-ministerial coordination is lacking despite the presence of a central policy framework. There is also a large gap between policy directives and on-the-ground implementation, which partly stems from Nepal's increasingly decentralized governance structure whereby the local government is increasingly responsible for creating and implementing energy plans. For example, in 2012, the Nepal government revised air pollution standards and vehicle emissions standards, but effective local implementation of those standards remains a challenge. Another common strand in most interviews was the need for strong clean air lobbying, to support existing efforts, namely from the Indoor Air Pollution and Health Forum and the AEPC's Nepal Alliance for Clean Cookstoves.

Policies related to specific cooking fuels and stoves

Firewood and other polluting fuels

According to the Nepal National Census 2011, close to 4 of Nepal's 5.4 million households (74.1%) currently use traditional biomass, including firewood, for cooking (Government of Nepal 2012). The Nepalese government thus considers biomass an important fuel, especially for rural populations. In particular, the Biomass Energy Strategy 2017, targeted primarily at rural Nepal, lays out a number of strategic measures, aiming to: "(a) Increase production of sustainable biomass energy by utilizing agriculture, forest residues and organic wastes; (b) Contribute to increased access to clean cooking technologies to all Nepalese households through the means of modern biomass energy; (c) Increase effectiveness and efficiency in the utilization and production of biomass energy; and (d) Partially substitute the utilization of diesel and petrol by bio-diesel and bio-ethanol" (Government of Nepal 2017).

In urban Nepal, however, primary reliance on solid fuel is only 31.5% (Demographic and Health Survey 2016; Government of Nepal 2012). In Kathmandu district, it is even lower, at 7.7% (Government of Nepal 2012), though some data sources suggest higher shares (Demographic and Health Survey 2016). If the districts of Lalitpur and Bhaktapur are included, primary solid fuel use in the urban Kathmandu Valley reaches only 11.4% (Government of Nepal 2012). At 2.9%, kerosene is a minor stove and fuel type in the valley (Government of Nepal 2012). Kerosene subsidies were eliminated in 2009, which partly explains this low use, but increased availability and promotion of LPG especially has also played a role. Nearly all stakeholders interviewed agreed that kerosene use in urban Kathmandu Valley, as of 2019, is very low. With the widespread availability of LPG today, and the increase in supply and quality of electricity over time, the share of solid fuels, particularly firewood, has also been decreasing in Kathmandu Valley.

Biomass-fuel Improved Cookstoves (ICS)

ICS were first introduced in Nepal in the 1950s and two main types are now available for household use: metallic ICS and rocket ICS (AEPC 2019). At the Renewable Energy Test Station (RETS), a public sector autonomous body, the efficiency of numerous ICS is tested and promoted. Most ICS in use in Nepal are Tier-II stoves that were provided to households in earthquake-affected districts, free of charge (Stakeholder Interviews 2019). Unlike other countries that have a market-based supply system for ICS, Nepal has a donor/development organization-based ICS push. The current subsidy regime greatly influences the biomass ICS market, with the government offering subsidies as high as 50% (Government of Nepal 2016). The government also recently launched its strategy for the higher efficiency Tier-III (and above) ICS, despite a lack of evidence that users would accept these stoves. Overall use of ICS remains limited, especially in Kathmandu Valley where biomass cooking is limited to a small share of the population. In urban areas, in fact, the government's focus on biomass ICS has been for institutional uses.

LPG

LPG is the most commonly used cooking fuel (67.7%) among urban Nepalese households (Government of Nepal 2012). In Kathmandu Valley, including districts of Kathmandu, Lalitpur and Bhaktapur, primary use of this LPG fuel reaches 84.3% (Government of Nepal 2012). Data for the fiscal year 2017-2018 from the NOC shows that 88% households in Kathmandu City have LPG cylinders. LPG imported from Indian Oil Corporation saw a 14.8% increase, on average, between the fiscal years 2008-2009 and 2017-2018 (Stakeholder Interviews, 2019). While the price of LPG fluctuates according to import prices, the government subsidy (on all LPG purchases) has remained relatively stable at 250-300 NPR/cylinder (Stakeholder Interviews 2019). Improved road connectivity is increasingly facilitating LPG penetration to peri-urban and rural areas.

Bhandari and Pandit (2018) estimate that demand for LPG fuel in Nepal in 2035 will reach 26.5 million GJ under a business-as-usual (BAU) scenario, i.e., with continued subsidization. Some energy experts interviewed for this study argued for phasing LPG out of the Nepalese market, just as the government phased kerosene out in 2002-2003. After the government's move to equalize the price of kerosene and diesel, in response to the massive adulteration of diesel for many years, kerosene use declined steadily over time. Experts argue that if LPG subsidies were to be removed and alternate clean cooking options be made widely available, LPG would similarly become a less preferred cooking fuel (Stakeholder Interviews 2019).

Electricity

Electricity use for cooking, which the government would like to see taken up, has historically been low; as of the 2011 Census, less than 1% of urban Nepalis used it as their primary fuel (Government of Nepal 2012). In 2015, during the trade blockade when LPG supply and other essential supplies (e.g. petrol, diesel, basic medicines) from India were rationed, many households in the Kathmandu Valley made a temporary switch to induction cookers and other electric cooking appliances, while others switched to using traditional and improved firewood stoves (Stakeholder Interviews, 2019). After the blockade was lifted, many of these households continued using electric stoves alongside LPG (Stakeholder Interviews, 2019). Anecdotally, vis-à-vis LPG, the initial stove cost for electric cooking may be high, but recurring fuel costs can be cheaper (Stakeholder Interviews, 2019). While there is a growing demand for electric stoves (there are currently 14-15 stove options on the market), the supply chain for electric stoves and appropriate kitchenware is nascent. In the absence of a strong supply chain, community rural electrification entities (CREEs) that manage electricity distribution within a community, may themselves act as local suppliers, and possibly develop partnerships with microfinance institutions (MFIs).[19]

With financial and technical support from CCA, the Nepal Bureau of Standards and Metrology (NBSM) has developed standards for electric cooktops appropriate for Nepal. On the federal government's behalf, AEPC is involved in implementing electric cooking standards.

There has been much less switching or experimentation with electric options in rural Nepal, owing to lack of consistent power supply from off-grid systems as well as the availability of biomass-based cooking alternatives. In previous electrification policies, providing grid electricity access for basic uses (e.g., lighting) was the government's prime focus. However, technical experts argue for utilization of already invested resources by allowing micro hydro plants to be grid-connected (World Bank 2015). AEPC now has an MoU with the NEA to develop sustainable micro-hydro projects, based on a principle of circling back revenue generation to communities and ensuring the viability of eventual grid connection.

Electricity generation, transmission capacity and distribution also remain major challenges facing electric cooking in Nepal. Bhandari and Pandit (2018) estimated that replacing LPG with electricity in 2035 would require an additional 1207 MW of installed electricity generation, if demand increases as expected. In 2014, 18% of Nepal's electricity was still imported from India (World Bank 2015). Utility companies have thus been reluctant to heavily promote electric cooking technologies given the additional load they would place on existing infrastructure (i.e. transmission lines, transformers and cables). Transmission lines were built without cooking-related energy consumption in mind, and the NEA and some international

---

[19] Across Nepal, there are a total of 282 CREEs in 52 districts serving more than 500,000 households. These CREEs have formed a national federation called National Association of Community Electricity Users (NACEUN). Details may be found here: https://naceun.org.np/. CREEs have been identified as the main institutional conduit for raising public awareness on electric cooking.

NGOs are not confident about promoting electric cooking.[20] Since cooking is energy-intensive, if households were to exclusively cook using electricity, back-of-the-envelope calculations suggest that a regular meal would require 1,000-1,200 W of electricity (Stakeholder Interviews 2019). To provide more context, 61% of Kathmandu Valley households have 5 Amp connections that are too low to support electric cooking using induction stoves, whose power capacity is approximately 2kW. Other impediments to electric cooking are unreliable electricity supply and voltage fluctuation, despite there being no declared power cuts and surplus power supply in Nepal (Stakeholder Interviews 2019).

Stakeholders interviewed were hopeful that after commissioning of hydropower projects (likely within the next 5-10 years), there may be surplus electricity that could support electric cooking. Nepal is currently mostly dependent on run-of-the-river technology for domestic electricity generation, and there is little excess capacity to deploy during peak hours. Electricity price reduction is an important policy instrument under consideration to encourage use of electric cooking but lowering prices would only increase demand and increase strain on current resources, and would also create cost recovery challenges for the utility.[21]

Some suggestions from stakeholders to promote electric cooking include: (a) Reducing tariffs for higher levels of electricity use (for cooking and domestic chores); (b) Lowering tariffs during peak cooking hours (i.e. 7am-9am and 6:30pm-9pm); (c) Installing Smart Meters; and (d) Transferring the existing subsidy for LPG to electricity.

The response of some national stove distributors and NGOs to clean cooking policies[22]

Firewood and other biomass

While there are few local NGOs working on cleaner biomass ICS in urban Nepal, due to lower use of biomass fuels there, three that are prominent in rural Nepal include: Center for Rural Technology-Nepal (CRT-N), Husk Power Nepal Pvt. Ltd. and Himalayan Naturals. These organizations assert that there is a market for higher tier ICS (biomass) stoves in Nepal, because agricultural residue and firewood remain important cooking fuels, even in the Kathmandu Valley. In partnership with Hivos and Energia, CRT-N works with community-based organizations to educate women in rural Nepal about the negative impacts of HAP and promote women's financial inclusion. It organizes training programs, seminars and workshops for both grassroots-level and higher-level organizations. Its partnership with CCA started in 2012, and recently completed a 1-year project with them on black carbon measurements (Weyant et al. 2019).

Husk Power Nepal Pvt. Ltd.'s new Tier-III forced draft ICS uses 2W electricity (easily supported by micro-hydro sources) and can also be used with a 5W solar panel and externally charged battery. The stove can accomodate any type of biomass (firewood, husks, crop residue and animal dung), and RETS rates its high power thermal efficiency at 41.2%. AEPC is planning to roll out these Tier-III stoves throughout the

---

[20] This newspaper article highlights some of NEA's challenges: https://kathmandupost.ekantipur.com/printedition/news/2016-06-03/more-power-to-the-people.html
[21] Current electricity tariffs in Nepal can be found here: https://nea.org.np/admin/assets/uploads/Consumer_Tarrif_data.pdf
[22] Appendix B2 summarizes the main stakeholders in Nepal's clean cooking energy sector.

Terai, where animal dung is used as a primary cooking fuel. Husk Power's beneficiaries are located across rural Nepal, and it has no urban presence owing to lack of subsidies in urban centers and low demand for the technology. Husk Power also works with NGOs focused on maternal and child health, such as Punarjagaran Samaj Nepal (also known as Renaissance Society Nepal), and with the Chief Minister's Office of Province No. 2, covering the eight districts of Bara, Dhanusha, Mahottari, Parsa, Rautahat, Saptari, Sarlahi and Sirahi in southeastern Nepal.

Husk Power uses three main channels to sell ICS: (i) Individual dealers who approach subsidy beneficiaries; (ii) partnerships with AEPC through a tendering process (wherein 50% subsidy is given to local manufacturers in rural areas only); and (iii) sale to international NGOs like Practical Action (14,600 Tier-II natural draft ICS were sold to them alone in 2018) and local governments (for the ultra-poor). In its sales pitch, Husk Power shows potential buyers the RETS certificate of extended stove run tests (Stakeholder Interviews 2019).

Responding to the electricity crisis in Nepal a decade ago, local NGOs like Himalayan Naturals promoted community-produced beehive briquettes in rural areas, using shrubs, twigs and other freely available forest biomass as feedstock. These briquettes were meant to support winter heating; but demand among households has declined as electricity supply has improved (the company continues to supply to restaurants and big retailers in urban areas). Until very recently, AEPC provided only training and no upgradation or enterprise support to briquette manufacturers.

Nepal Energy Foundation's (NEF) core programs are focused on knowledge generation, capacity building, research activities, training and awareness around clean energy. In urban areas, their work is mainly on energy efficiency; involving women in the energy sector, especially in municipal governments; standards for safety of household electricity uses; and raising awareness of electrical hazards. Extending their prior experience with biogas, they also plan on piloting an intensified pellet production project that would provide local employment in a to-be-determined location. NEF is particularly considering integration of forest user groups into this pilot program, which would mainly cater to rural Nepalese households currently using biomass for cooking.

The government's rigid tax regime, however, typically makes it difficult for local stove manufacturing and distribution companies to thrive. While companies importing stoves pay only a 1% tax, local stove manufacturing companies pay varying taxes depending on the nature of the imported inputs they use. For example, there is a 48% custom duty on fans used in ICS, 36% custom duty for stove handles and 16% custom duty for steel. These tariffs make it difficult for companies to remain competitive. Even more than regular financial support from the government, the company desires enforcement of clear technology standards that would aid domestic ICS manufacturers, for example.

Electricity

In Nepal, AEPC carries the mandate for clean cooking and energy efficiency, especially with renewables including electric cooking. CCA facilitated the process for developing standards for electric cooktops and implementation strategy by the Nepal Bureau of Standards and Meteorology (NBSM) with technical support from NEF. Stakeholders interviewed also emphasized the need for establishing testing stations or laboratories to verify the quality of imported electric cookstoves.

To reduce HAP, the Ajummery Bikas Foundation (ABF) explained in stakeholder interviews (2019) that it has initiated an electric cooking demonstration project and begun to develop an implementation strategy for electric cooking. In January 2019, ABF, National Association of Community Electricity Users Nepal (NACEUN) and Radio Sagarmatha, jointly launched a 5-year national campaign with electric stove suppliers to promote energy-efficient electric cooking in CREE areas.[23] This effort targets 3,000 households in 10 CREEs in the first year (2019), followed by scaling to fifty CREEs and more than 15,000 households in the second year (2020). By 2023 (fifth year), all electrified CREEs will be involved in electric cooking, covering over 150,000 households (ABF 2019). As of January 2020, the Campaign has been able to promote over 750 electric cooktop packages across three CREEs i.e. two in Kavrepalanchok district and one in Banke district of Nepal. The campaign promotes a bundle of products along with induction stove tops, including pressure cooker and saucepan. ABF's campaign currently lacks external support but is hoping to leverage financial support from international NGOs, local governments and private sectors to realize the above targets to increase the cost, scope, and speed of scaling of its program.

Other relevant activities

Organizations such as Clean Air Network-Nepal (CANN) have conducted campaigns to create awareness about the air pollution problem in the Kathmandu Valley. In 2018, along with the International Center for Integrated Mountain Development (ICIMOD), CANN organized a mayors' summit to develop an action plan to reduce air pollution in the Kathmandu Valley. Civil society organizations such as Drishti Kathmandu have developed their own network of low-cost sensors and made real-time air quality data publicly accessible. Nepal's Ministry of Forests and Environment monitors air quality throughout the country, and the U.S. Embassy has installed two air quality monitors in Kathmandu (Government of Nepal 2020; U.S. Embassy in Nepal 2020).

The response of international NGOs and donors to clean cooking policies

In Nepal, the Asian Development Bank (ADB) is the foremost power sector partner, especially in providing guidance and financing for NEA's generation, transmission and distribution investments. On the distribution side, ADB assists with increasing access, reorienting small hydropower plants, and supporting solar street and energy-efficient lighting. It has also supported rural electrification (ADB 2017).

The WHO has proposed including Kathmandu under its Urban Health Initiative owing to high ambient air pollution from the transport sector, industrial sources, solid waste burning and HAP. WHO has primarily been involved in advocacy, dissemination, and promoting use of clean cooking technologies. Using communication products, they are attempting to bridge the divide between researchers (given that close to 130 studies have been conducted to date in and around the Kathmandu Valley) and the central government (as the latter is unaware of research results), to aid government setting of realistic targets (Stakeholder Interviews 2019).

---

[23] ABF envisions its campaign to work with various direct and indirect clean cooking stakeholders, namely, (i) training and academic institutions for capacity building; (ii) banks and financial institutions for consumer financing; (iii) development organizations for developing and implementing electric cooking programs; (iv) all government levels needed for policy support, coordination and budget allocation for electric cooking; and (v) private sector suppliers for marketing of high-quality electric cooking products (ABF 2019).

The Atmosphere program at ICIMOD helped the Ministry of Forests and Environment with the design of Nepal's existing air pollution monitoring network. Among other training programs, ICIMOD has conducted a week-long training for journalists and another for brick kiln owners. The program is generally interested in residential HAP research but does not currently have any ongoing projects in this domain.

Donor agencies like GIZ that currently work in several provinces (Provinces 3 and 4: Chitwan, Parvat, Makwanpur Districts) have sold close to 35,000 portable ICS (Tier-II) stoves. GIZ works in close collaboration with AEPC, RETS and local government units for their stove promotion programs in rural Nepal. GIZ's EnDev project, with Practical Action as the implementing partner, aims to (i) support a private sector-led clean cookstove marketing approach and relevant supply chain development support; and (ii) reduce respiratory health problems in Nepal caused by HAP. The project also seeks to provide loans through cooperatives (GIZ 2017).

Practical Action has a Nepal-specific ICS program, supported by the GIZ EnDev program. While it began with promotion of Tier II firewood ICS, it now offers Tier II and III stoves (natural and forced draft stoves). It follows two types of marketing campaigns: issue- and supplier-based. In the former, using radio, pamphlets, and videos with local NGOs, Practical Action focuses on health improvements, time savings and protection of forests from ICS use. In the latter, suppliers themselves are responsible for product marketing.

Summary

Both Kenya and Nepal display a long history of policy development and program implementation aimed at spurring the uptake of improved and clean cooking technologies. Within these countries, Nairobi and Kathmandu represent large cities where clean fuels are very widely, but not universally, used. In fact, the persistence of solid and polluting fuels in these settings – charcoal and kerosene in Nairobi, and firewood in Kathmandu – is a vexing reminder that specific initiatives remain necessary to complete the energy transition even in large cities in less-developed countries. In the remainder of this report, we describe an analytical framework aimed at a) quantifying the burdens imposed by the current situation, in terms of time lost due to use of inefficient technology, as well as health and environmental damages, then b) analyzing the case for different interventions, and finally c) distilling these results into a set of policy recommendations.

Analytical Framework

We now present the overarching analytical framework that we leverage to provide understanding of the key features and assumptions implicit in our approach. Similar to the Jeuland and Pattanayak (2012) and Jeuland, Tan Soo and Shindell (2018) (hereafter JP and JTS), we develop equations that allow calculation of the costs and benefits associated with various clean cooking choices (Tables 1 and 2). The equations have been modified to account for the city-scale of the analysis, and to accommodate inclusion of specific policy interventions that are explored in the policy analysis in each location. A key modification in this set-up, relative to JP and JTS, is to incorporate accounting for the contribution of domestic fuel burning to ambient $PM_{2.5}$ concentrations and exposures. This is particularly relevant in urban areas where exposures to pollution are not as strongly influenced by household cooking as those in the rural environments where traditional cooking technologies dominate. A second key modification is to allow aggregation of costs and benefits at the city level, which involves multiplying the number of new clean energy users (i.e., those transitioning away from polluting options) in each cooking scenario. A third key modification is to characterize the costs and benefits of specific policies (e.g., subsidies or polluting fuel ban), based on the likely behavioral responses they would engender.

Finally, a fourth relevant consideration is that we include several transitions that were not considered in previous analyses, crafted in response to feedback obtained in the in-country stakeholder interviews about the most relevant options to consider in each city.[24] We compare changes that would result from the following specific transitions, were they to reach all those currently using a particular less clean option. Table 3 summarizes the cooking transitions under consideration in each location, which are also further described below in the section entitled “Description of cooking transitions and data sources”. In Nairobi, transition 1 represents a partial move towards a cleaner option, whereas transitions 2 through 5 consist of a move from dirty fuels to clean fuels, though for different populations (charcoal users in transitions 2 and 4, and kerosene users in transitions 3 and 5). Likewise, in Kathmandu Valley, transition 1 is a limited move towards cleaner cooking, transitions 2 and 3 consist of movement from a solid fuel to clean fuels, and transitions 4 and 5 are between two clean fuels[25].

---

[24] The new transitions include switching from charcoal to ethanol, switching from kerosene to ethanol (only in Kenya); as well as switching from LPG to electricity, and the corresponding switch from electricity to LPG (the latter two only in Nepal).

[25] Our analysis is focused on electric cooking technologies that can replace other technologies like traditional firewood stoves, ICS and LPG. While electric rice cooker is an option, all cooking cannot be done on it. Electric coil stoves are another option, but there have been advancements in technology, and induction stoves are more efficient, safe and convenient to use than electric coil stoves. Moreover, they are the most common and popular electric cooking option in Kathmandu Valley. Therefore, in our analysis, by electric stoves, we refer to induction stoves, acknowledging that they are only a subset of electric stove options.

Table 1. Typology of costs and benefits of clean cooking transitions (adapted from JTS)

Costs	Examples	Benefits	Examples
Privately borne (included in analysis)			
Capital ("hardware")	Cost of new technologies: Improved charcoal stoves, LPG and ethanol stoves; cooking space improvements; etc.	Morbidity mortality reductions	Benefits from reduced incidence of and mortality from disease (acute lower respiratory infections; COPD; IHD, stroke lung cancer)
Program ("software")	Cost of implementation: Marketing and promotion materials; government/private company staff time; etc.	Time savings	Benefits of reduced cooking time (resulting from efficient heating)
Operation and maintenance	Cost of replacing/cleaning of equipment, including time		
Fuel used in new stove	Cost of fuel, in collection and preparation time and/or money	Fuel no longer used in old stove	Cost of fuel, in collection and preparation time and/or money
Learning and tastes	Costs of familiarization with the use of a new stove technology; loss of value from modified taste		
Socially borne (included in analysis)			
		Spillover morbidity and mortality reductions	Benefits from reduced incidence of and mortality from diseases (stated above) due to reduced ambient air pollution
		Climate- and ecosystem-related	Benefits from reduced emission of black carbon and lesser tree cutting

The unit of analysis for our calculations is the whole of Nairobi city (in Case 1) and whole of Kathmandu Valley, including the cities of Kathmandu, Lalitpur and Bhaktapur (in Case 2). We first carry our calculations that abstract from policy effectiveness and illustrate the potential gains from each specific transition. In those illustrative calculations, the aim is to quantify the various burdens stemming from use of lower quality stoves and fuels. We thus compare the monthly costs of a complete switch to exclusive use of the newer technology with the monthly economic benefits that a household would receive. In the investment analysis, we then account for partial uptake and use of cleaner cookstoves as these are affected by prices and other factors, similar to a real-world effectiveness, to examine how policy interventions would likely shift behavior, and to give a sense of how much of this potential can be achieved by the different intervention strategies.

Table 2. Equations for costs and benefits included in analysis

Equations		Appendix equation #
Costs		
Cap	$Cap = SW \cdot s^c \cdot (cc_i \cdot crf)/12$	(B1)
Prog	$Prog = SW \cdot cp/12$	(B3)
O&M	$O\&M = TotalPopn \cdot \chi_i \cdot ((Main_i - Main_0)/12)$	(B4)
Learn	$Learn = SW \cdot l \cdot v^t \cdot crf/12$	(B5)
Fuel	See Appendix for detailed derivation and discussion. For baseline: $Fuelc_0 = TotalPopn \cdot [(Fuelu_0 \cdot \chi_0 \cdot p_0)]$ For improved/clean: $Fuelc_i = TotalPopn \cdot [Fuelu_i \cdot \chi_i \cdot p_i \cdot ft_i]$	
Benefits		
Timesav	$Timesav = TotalPopn \cdot 30 \cdot time_0 \cdot \chi \cdot (1 - te_i)$	(B7)
Morb	$Morb = SW \cdot (1+\pi) \cdot \sum_k (\sum_{t=1}^{5} CL_t \cdot (hhsize \cdot (PAF_0 - PAF_i) \cdot IR_k)/(1+\delta)^{t-1})$	(B18)
Mort	$Mort = SW \cdot (1+\pi) \cdot \sum_k (\sum_{t=1}^{5} CL_t \cdot (hhsize \cdot (PAF_0 - PAF_i) \cdot MR_k)/(1+\delta)^{t-1})$	(B19)
Clim	$Clim = TotalPopn \cdot \chi \cdot \left(fuelu_0 \cdot GWP_{i,m} \cdot \mu_m \cdot \varepsilon f_0 - fuelu_i \cdot GWP_{i,m} \cdot \mu_{i,m} \cdot \varepsilon f_i\right)$	(B23)
Bio	$Bio = TotalPopn \cdot \chi \cdot (1 - \psi) \cdot (fuelu_0 - fuelu_i)$	(B24)

Notes: Parameters are as defined in Table B1, and their values are summarized in Tables C1-30.

Table 3. Summary of cooking transitions

Transition No.	Nairobi	Kathmandu Valley
1	Traditional charcoal to charcoal ICS	Traditional firewood to natural draft ICS
2	All charcoal to LPG	Traditional firewood to LPG
3	Kerosene to LPG	Traditional firewood to electricity
4	All charcoal to ethanol	LPG to electricity
5	Kerosene to ethanol	Electricity to LPG

We incorporate the following commonly-used policy instruments for spurring clean cooking into our analysis: stove subsidy, fuel subsidy, stove finance, BCC, and fuel bans. Table 4 summarizes transitions where each of these policy interventions is applicable, in both locations. While subsidies, market development, and awareness creation have been discussed extensively in the clean cooking sector (Rosenthal et al. 2018), empirical studies on such interventions' impacts are limited (Evans et al. 2020).

Recent experimental studies have shown ICS demand to be strongly responsive to subsidies, financing, and supply chain development (Pattanayak et al. 2019). Financing alone increases demand, while BCC is found to have limited effects on willingness to pay (Beltramo et al. 2015). Levine et al. (2015) show that combining a free trial, time payments and allowing risk-free returns of stoves increased adoption of charcoal ICS by rural Ugandan households. Usmani et al. (2017) demonstrated that economic incentives (i.e., stove use subsidies and rebates) facilitate initial ICS adoption in rural Cambodia but do not necessarily induce stove use in the long-run. National-level subsidies have also been shown to encourage the transition to clean cooking, for example in Indonesia (Budya and Arofat 2011; Imelda 2019) and Ecuador (Troncoso and da Silva 2017), where they have facilitated uptake of LPG. Subsidies alone have not been found to eliminate stacking, however (Gould et al. 2018). In measuring the costs of policies to provide LPG to South Asians, Cameron et al. (2016) argue that the most cost-effective policies typically require large stove subsidies.

Table 4. Summary of policy interventions

	Transitions applicable	
Policy Intervention	**Nairobi**	**Kathmandu Valley**
Stove subsidy only	All	All
Fuel subsidy (w/ stove subsidy)	All except Traditional charcoal to charcoal ICS (T1)	All except Traditional firewood to natural draft ICS (T1)
Stove financing (w/ stove subsidy)	All	All
Behavior change communication (BCC) (w/ stove subsidy)	All	All
Polluting fuel ban	All	All except LPG to electricity (T4) and Electricity to LPG (T5)

A prior model on which we draw heavily, presented in JTS, used descriptive cost-benefit simulations to show that stove subsidies shift the private net benefits of transitions to cleaner transitions strongly, but that private benefits may nonetheless remain negative for many technologies and households. This implies that even free distribution of stoves may not be sufficient for socially optimal take-up and use. Urban charcoal users can be highly price sensitive (Kebede et al. 2002). Studies have argued that LPG price subsidies reduce firewood use (Ouedraogo 2006), but LPG is much more likely to be used by the rich, unless specifically targeted to low-income populations (Bacon et al. 2010). Gupta and Köhlin (2006) found that owing to cross-price elasticities, fuel subsidies in India would be less likely to reduce demand for polluting fuels like coal and firewood, and that improved LPG availability and HAP awareness would be needed to increase demand. Relevant evidence from India's recent LPG subsidy expansion program indicates a large increase in the number of LPG users, but refill rates have fallen short of the levels needed to achieve substantial HAP reductions (Kar et al. 2019).

Heavier regulatory action (e.g., fuel use bans) has also been attempted for some fuels in some contexts. Under China's coal-to-electricity program that bans coal and provides subsidies for electricity and electric heat pumps, households in high- and middle-income districts have largely eliminated coal, but low-income districts continue to lag behind (Barrington-Leigh et al. 2019). Pachauri (2019) argues that policies encouraging clean fuel use are often not sufficiently targeted to low-income households.

Finally, the effects of BCC campaigns on cleaner cooking outcomes have been mixed. In a review, Goodwin et al. (2015) found only mixed evidence of impacts of BCC techniques (e.g., shaping knowledge, reward and threat, social support, comparisons) on clean stove uptake, health and environmental outcomes. As noted above, Beltramo et al. (2015) only observe a small (roughly 10%) increase in demand for cleaner technology with randomized exposure to health-related and other marketing messages.

In keeping with JTS, we apply a net benefits criterion to compare the overall economic net benefits of different policy interventions developed to foster these transitions (Boardman et al. 2005). Our assessment is conducted from both private and social welfare standpoints. For the private standpoint, we only include the costs and benefits that households making the transition incur. The social perspective includes the former plus any changes in the effect of various transitions on carbon emissions and forest loss owing to unsustainable charcoal harvesting.

The costs included in the final analysis pertain to equipment (capital costs), program expenses related to distribution and marketing, time and money spent on operation and maintenance of stoves, learning costs, and the difference in net fuel costs from use of the original and new technology. The equations for the calculation of these costs are detailed in Appendix C. On the benefits side, we include improved health and cooking time savings, and climate-linked environmental social benefits from reduced black carbon or greenhouse gas emissions and deforestation. The total costs and benefits are the sum of respective components.

Our framework relies on various assumptions, as is common to cost-benefit simulation efforts. The first, largely validated by data from various sources, is that households primarily use five cooking technologies in Nairobi, namely traditional charcoal stoves, improved charcoal stoves, kerosene, LPG and ethanol. In Kathmandu Valley, we consider three primary cooking technologies namely traditional firewood stoves, LPG and electricity. While this is based on data in the literature and from interviews conducted in both cities, we exclude clean technologies that may be used in very low proportions (e.g., electric stoves and biogas in Nairobi, and improved firewood cookstoves and biogas in Kathmandu Valley). Our second assumption relates to input parameters in our model. As the Nairobi- and Kathmandu-specific literature on the required parameters for this analysis is sparse, we also transfer estimates from urban East Africa and urban South Asia, respectively, or global estimates, wherever data are limited. Details of parameters used in our analysis are in Appendices D and E. Here we highlight that there is relatively little information available regarding the costs of our specific policy interventions – financing, behavior change campaigns, technology bans, and subsidy leakage – so we make a number of simplifying assumptions about these that are worth highlighting here. For financing, we assume an additional 10% cost incurred to acquire technology, and BCC is assumed to cost $10 per household targeted. Stove subsidies are assumed to have 25% leakage, while fuel subsidies, which are more challenging to manage, have 50% leakage. Finally, a technology ban is estimated to cost $17 per household per year, which is equivalent to the upper bound of program costs documented in Jeuland et al. (2018).

Third, similar to JP and JTS, we value time costs and benefits as a fraction of the unskilled wage rate in Kenya and Nepal. We do not include the inconvenience costs of clean cooking options or the aesthetic benefits they may provide, due to the relative dearth of careful valuation work on these aspects. Fourth, we include only five HAP-related diseases for which there is substantial evidence in the literature: chronic obstructive pulmonary disease (COPD), acute lower respiratory infection (ALRI), ischemic heart disease

(IHD), stroke and lung cancer (LC). We exclude the harmful effects of pollutants other than $PM_{2.5}$ (Smith et al. 2013; Zhang and Smith 1999). Following JTS, we assume that mortality reductions are from reduced $PM_{2.5}$ exposure (Burnett et al. 2014), and that relative morbidity risks for exposed populations are reduced similarly to those for mortality. The estimated contribution of health improvements to the disease burden form the basis for estimates for health spillovers from ambient air quality improvements (Chaffe et al. 2014). To value health improvements, we apply the cost-of-illness (COI) per case/per year for morbidity and value of a statistical life (VSL) for reduced mortality (Viscusi and Aldy 2003).

Fifth, given Nepal's clean electricity generation (from hydropower), unlike many countries that use non-renewable sources for electricity generation (e.g., coal, gas, nuclear and oil), we assume that the electricity emissions for all pollutants considered in our analysis (i.e. CO_2, CH_4, N_2O, CO, BC and OC) are nil. Sixth, our valuation of environmental benefits relies on the social cost of carbon (Interagency Working Group on Social Cost of Carbon 2015). Though we use the replacement cost of trees to account for deforestation and degradation, we ignore valuation of ecosystem services owing to data paucity (Ferraro et al. 2011). Seventh, due to the limited data on ethanol stoves particularly on pollutant exposures, we use LPG input parameters as the two stoves have comparable exposure levels. Still related to ethanol, we do not include environmental impacts or other externalities that would arise from conversion of land to ethanol production, wherever these may occur (whether from local or imported ethanol). Finally, we assume that the time efficiency of LPG and electric stoves with respect to each other are the same.

In our literature search, the parameters for which there was limited to no evidence are: time spent cooking on various stoves, time efficiency of LPG and ethanol stoves with respect to charcoal stoves, accurate prices of various ICS, LPG and ethanol stoves and fuels, rate of usage of stoves (versus rate of usage of fuels, which is what we use in our analysis), learning and maintenance costs of all stoves. In May 2019, we conducted a targeted data collection effort in 354 households from four informal settlements in Nairobi. In late July-mid August 2019, we conducted a targeted data collection effort in 360 households from peri-urban areas in Kathmandu Valley (covering districts of Kathmandu, Lalitpur and Bhaktapur). In both sites, in addition to asking questions aimed at specifying parameters that are not available in the literature, we included a stated preference experiment to assess households' price sensitivity for proposed transitional (i.e. kerosene) or clean cooking technologies (i.e. LPG, electricity and ethanol), which is crucial for our eventual prediction of the effects of pricing policies, in the investment cases analyses. These data are described in additional detail in the section entitled "Description of cooking transitions and data sources".

Description of cooking transitions and data sources

Focus City in Sub-Saharan Africa: Nairobi, Kenya

This section describes in additional detail the five possible cooking technology transitions included in the clean cooking investment analyses for Nairobi.

Transition 1: Traditional charcoal stove users shifting to charcoal ICS. As described previously, charcoal is the primary cooking fuel for nearly 17% of urban Kenyans (CCAK and MoE 2019). While 5% of Nairobi's population uses charcoal as a primary cooking fuel, 20% of households in Nairobi use charcoal as a secondary cooking fuel (ibid). Despite recent increases in charcoal prices in Nairobi, use of inefficient traditional charcoal stoves is prevalent especially among low-income households, while charcoal ICS are most widely used among middle- and higher-income groups. For low-income users of charcoal who still rely on traditional stoves, a cooking transition worth considering is towards universal use of charcoal ICS, which cost more than traditional charcoal stoves but perform better in terms of fuel efficiency, therefore requiring less charcoal per day and lower recurring costs. Charcoal ICS also emit less pollution ($PM_{2.5}$, CO2, CH4, N2O, CO, BC, OC) than traditional charcoal stoves, with implications for health and the climate. Stove manufacturers and distributors note that demand for charcoal ICS is high in urban Kenya, given the fuel and money savings these allow over the longer term. To facilitate this transition, we consider the following policy instruments: stove subsidy only, stove subsidy with stove financing, stove subsidy with BCC campaign, and a ban on traditional charcoal stoves. We consider that a stove plus fuel subsidy intervention is not viable for spurring this transition, because a fuel subsidy would also reduce the recurring cost of using traditional charcoal stoves, thereby undermining the principal goal of the intervention.

Transition 2: Charcoal users shifting to LPG. A different cooking transition, which could include both users of traditional and ICS charcoal technologies, would be to move towards use of the main clean fuel alternative, LPG. This transition is especially relevant because the government is scaling up efforts to improve access to, and reduce prices of, LPG. An increase in the number of LPG cylinder manufacturers and distributors, regulation of gas cylinder exchanges, launching of the pay-as-you-go model, and greater availability of LPG cylinders in small sizes (1kg and 3 kg) all make LPG a more accessible clean cooking option. LPG stoves and fuel are more expensive than charcoal ICS but provide much more effective energy conversion and heating. LPG stoves emit far fewer pollutants than charcoal ICS, but have higher fuel transport and supply chain costs. A key advantage of LPG relative to ethanol (see transition 4) is the fact that it is a relatively well-known fuel. To facilitate this transition, we consider all five policy instruments: stove subsidy only, stove subsidy and fuel subsidy, stove subsidy with stove financing, stove subsidy with BCC campaign, and a ban on kerosene stoves.

Transition 3: Kerosene users shifting to LPG. After LPG, kerosene is still the most widely used primary cooking fuel in Nairobi (CCAK and MoE 2019). Yet rising kerosene prices following equalization of the kerosene and diesel excise duty (16%) make a transition away from this fuel more probable. A key question is whether users will revert to charcoal or make the cleaner transition to LPG. Compared to charcoal ICS, LPG stoves are more expensive (to purchase and maintain), but are more time, fuel and energy efficient than charcoal ICS. Pollutant exposures and relative disease risks are also considerably lower in LPG stoves than kerosene or charcoal stoves. The five policy instruments previously described to induce LPG cooking are incorporated here as well.

Transition 4: Charcoal users shifting to ethanol. Another option for a transition to clean cooking technology by charcoal users would be ethanol. Though the market for ethanol stoves is small and current government regulations (25% effective duty) make it an expensive fuel, some have argued that ethanol could be the cheapest clean cooking fuel option for Kenyans (Dalberg 2018). The fuel is currently mostly imported, and therefore not substantially different from an energy security perspective, but it could potentially be produced in Kenya (Stakeholder Interviews, 2018). Ethanol stoves cost more than charcoal ICS, but like LPG stoves are high on time, fuel and energy efficiency. Their emissions are considerably lower than for any charcoal stoves and are similar to LPG. Similar to transition 2, we include all five policy instruments.

Transition 5: Kerosene users shifting to ethanol. By virtue of already using a liquid fuel, kerosene users are a main target for ethanol companies. Therefore, our last clean cooking transition under consideration is from kerosene to ethanol. Mirroring transition 3, all five policy options are included.

Focus City in South Asia: Kathmandu, Nepal

We now describe the five possible cooking technology transitions included in the investment analyses for the Kathmandu Valley.

Transition 1: Traditional firewood stove users shifting to improved firewood cookstoves (natural draft). Though firewood forms a small share (we assume 11.4% accounting for stacking and variation across data sources, as described further below) of the cooking fuel mix in the Kathmandu Valley (including Kathmandu, Bhaktapur and Lalitpur), it is nonetheless important to consider a potential transition to natural draft ICS. This shift may be especially relevant for peri-urban households in the region that have access to freely available firewood from nearby forests. To facilitate this transition, similar to transition 1 for Nairobi, we consider the following policy instruments: stove subsidy only, stove subsidy with stove financing, stove subsidy with BCC campaign, and a ban on traditional charcoal stoves. We do not consider fuelwood subsidies to be a viable option, given that many households collect fuel, and that subsidies would anyhow encourage traditional as well as improved biomass stove use.

Transition 2: Traditional firewood stove users shifting to LPG. Given the government's push for clean energy, the next transition we model is for all existing firewood users moving to LPG – currently the most widely used clean cooking fuel in the Kathmandu Valley. While the initial cost of an LPG stove and subsequent LPG refills is higher than that of a biomass-burning stoves, LPG emits significantly fewer health- and environment-damaging pollutants ($CO2$, $CH4$, $N2O$, CO, BC and OC). Identical to LPG promotion in Nairobi, five policy instruments are considered for spurring this transition: stove subsidy only, stove subsidy and fuel subsidy, stove subsidy with stove financing, stove subsidy with BCC campaign, and a ban on traditional firewood stoves.

Transition 3: Traditional firewood stove users shifting to electricity. The move from traditional firewood-burning stoves to electricity is aligned with the Nepal government's vision of building energy independence through hydropower-generation. Electricity infrastructure as it currently stands cannot support universal electric cooking, though the government is looking to develop such infrastructure moving forward. Thus, the proportion of electricity users for cooking, low (0.1%) in the last Census of 2011, has been increasing, especially since the 2015 Nepal blockade. Like LPG, HAP emissions from electricity generation are lower than from firewood, as are relative health risks. This transition could be facilitated through all 5 policy interventions described above.

Transition 4: LPG users shifting to electricity. During the 2015 blockade, some urban households in Nepal, especially in Kathmandu, coped with shortages of LPG by turning to electric cooking, though the induction stoves that would fully replace LPG stoves remain in limited use. Even after the blockade ended, some households continued using a mix of LPG and electrical devices, especially rice cookers. Various stakeholders noted that they see more complete electric cooking as the future—given the government's clean energy policy direction and desire to lower dependence on LPG imports, urban households' preferences for the same, a growing market for electric stovetops and non-governmental organizations' development of BCC campaigns encouraging electric cooking. For this transition, we consider four policy options aimed at spurring use of induction stoves: stove subsidy only, stove subsidy and fuel subsidy, stove subsidy with stove financing, and stove subsidy with BCC campaign. A ban on LPG stoves is not practical and might be counterproductive in moving households back to firewood, and has therefore been excluded.

Transition 5: Electric cooking users shifting to LPG. Given households' differing preferences for cooking stoves and fuels, it is also worth considering a transition back to LPG from use of electric stoves. Some reasons for reverting to LPG could be high cost of electricity, misalignment with cooking preferences, and the government's need to ration limited electricity supplies, among others. This transition considers the same four policy options included in transition 4.

Data Sources and Model Parameters

In Table 5, we present a summary of the parameters included in our models. To get representative data for relevant populations in both cities, we drew from both primary and available secondary data sources. Nairobi-specific data for primary stove options and stove costs were obtained from the most recent Kenya National Cooking Sector Study (2019). Cooking time (charcoal and kerosene stoves), the proportion of traditional charcoal and ICS charcoal stove users, fuel collection times and market prices of fuels were collected through Duke University's survey – carried out to support this work and supported by CCA – in Nairobi's four main informal settlements (2019). Demographic parameters such as household size and household composition were taken from the urban sample of the Kenya National Cooking Sector Study (2019).

Table 5. Parameter definitions and units

Parameter	Description	Unit	Source
c_i^c	Cost of stove type *i*	U.S.$/stove	Clean Cooking Catalog, Stakeholder interviews (2018, 2019), Daraz website, Envirofit Retail Price List (2018), Burn Manufacturing Website (2018), Cookswell Jiko Website (2018), Dalberg Report (2018), Total Price List (2013)
c^p	Program cost of promotion	U.S.$/hh-yr	JTS (2018)
c_i^m	Cost of stove maintenance	U.S.$/hh-yr	JTS (2018)
T_i	Lifespan of stove *i*	yrs	JTS (2018)
χ	Rate of use of cooking stove option	%	Nepal Census (2011), Demographic and Health Surveys, Nepal (2016), Kenya National Bureau of Statistics (2018), Dalberg Report (2013)
$cook_0$	Average daily cooking time with baseline stove	hrs/day	JTS (2018)
te_i	Time efficiency of stove *i* relative to baseline stove	Unitless ratio	JTS (2018), Dalberg Report (2018)
ϵf_i	Fuel efficiency of stove *i*	MJ useful/MJ heat[1]	JTS (2018), Daraz website
μ_i	Calorific value for stove *i*	MJ/kg fuel[2]	JTS (2018)
$fuelckg_0$	Amount of fuel used for cooking; baseline stove	kg/hr	JTS (2018)
f	Percentage of people buying baseline fuel	%	Nepal Census (2011), Demographic and Health Surveys, Nepal (2016), Kenya National Bureau of Statistics (2018)
$collt_0$	Average daily baseline fuel collection time	hrs/day	JTS (2018)
κ^t	Shadow value of time spent cooking (fraction of wage)	Fraction	JTS (2018)
W	Unskilled market wage	U.S.$/hr	JTS (2018), Wikipedia
inf	Inflation rate	%	JTS (2018), Wikipedia
δ_{carb}	Discount factor for 2015 carbon price	%	JTS (2018)
$prep$	Average daily fuel preparation time for ICS stove	hrs/day	JTS (2018)
p_i	Cost of fuel type *i*	$/kg[3]	JTS (2018), Nepal Oil Corporation (2014-2019); Stakeholder interviews (2019), Total Price List (2013)
l	Learning hours	hrs	JTS (2018)
ft_i	Liquid fuel transport cost	$/kg	JTS (2018)
IR_k	Incidence/prevalence of disease *k*	cases/100	GBD (2017), Smith & Mehta (2000), GHE (2014)
MR_k	Mortality rate due to disease *d*	deaths/10000	GBD (2017), WHO (2014)
COI_k	Cost-of-illness of disease *d*	U.S.$/case	JTS (2018)
π	Health spillover parameter	None	JTS (2018)
ε_i	Exposure adjustment parameter for stove *i*	None	JTS (2018)
c^{co_2}	Cost of carbon emissions	U.S.$/ton	JTS (2018)
ψ	% of biomass harvesting that is non-renewable	%	JTS (2018)
$treecost$	Tree replacement cost	$/kg	JTS (2018)
$hhsize$	Number of persons per household	persons/hh	Nepal Census 2011; Kenya National Bureau of Statistics Report 2015-2016

sfu	% of households using solid fuels	%	Nepal Census 2011; Kenya National Bureau of Statistics Report 2015-2016, Dalberg Report (2013)
δ_s	Discount rate (social)	%	JTS (2018)
δ_p	Discount rate (private)	%	JTS (2018)
$\varepsilon_{PM_{2.5,i,m}}$	Particulate emissions for stove *i* and fuel *m*	24-hr μg/m^3 $PM_{2.5}$	Pope et al. (Ongoing meta-analysis), JTS (2018)
$\varepsilon_{j,i,m}$	Emissions factor for pollutant *j* from stove *i* and fuel *m*	g/MJ fuel	JTS (2018)
VSL	Value of statistical life		JTS (2018)
$sapp$	Source apportionment: HAP as a proportion of AAP	Fraction	Karagulian et al. 2015
$ambconc$	Daily average $PM_{2.5}$ concentration in each city	μg/m^3	Government of Nepal, Ministry of Population and Environment, Department of Environment Air Quality Monitoring; Nairobi Air Quality Monitor-US EPA, Air Now-US EPA & World Air Quality Index Project 2019
$ambexp$	Average ambient $PM_{2.5}$ exposure (24-hr) from cooking	μg/m^3	Calculated
$tothh$	Number of households in the city	None	Nepal Census 2011; Kenya National Bureau of Statistics Report 2015-2016

Notes: [1] For electricity, kW-hr/hr, [2] For electricity, MJ/kW-hr, [3] For electricity, $/kW-hr

Duke University's parallel survey in peri-urban areas of Kathmandu Valley (2019) informed our parameters on time spent cooking on various stoves in that site, cost and lifespan of stoves, and market prices of fuels. The most recent Nepal Census (2011) data for urban areas provides estimates of the distribution of primary cooking stoves, household size and number of children under five.

For both cities, we were able to find publicly available data on daily average ambient $PM_{2.5}$ concentrations. Using a published estimate of source apportionment in SA and SSA, we then calculated the approximate average $PM_{2.5}$ exposure (24-hours) due to cooking with different technologies in each location. Finally, several health parameters – disease prevalence/incidence, mortality rates – were not available at the city-level, so we used national-level estimates from the Global Burden of Disease. As noted in Table 5, several additional parameters were sourced from regional or global sources used by the prior JP and JTS studies. Examples of these include: program costs of stove promotion, calorific value of fuels, shadow value of time spent cooking, learning hours, liquid fuel transport, and cost of carbon emissions. For additional details on data sources, please see Appendices D and E).

Results

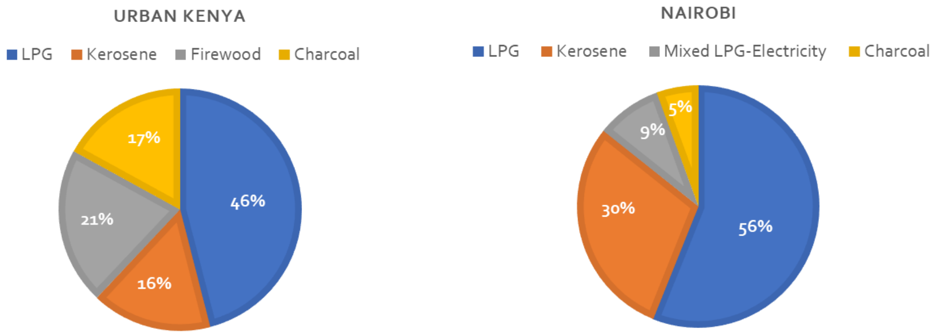
This section presents the results of our city case analyses: Nairobi first, and then the Kathmandu Valley. In both cases, we begin by discussing baseline (or current) conditions, and the burdens associated with existing use of solid or polluting fuels. This includes presentation of the corresponding potential – which assumes a complete transition from the baseline technology to cleaner solutions – of each transition considered using our framework. We then turn to the policy-specific results under each of those transitions. The latter analysis allows the characterization of the extent to which the potential of various transitions might be achieved using different policy instruments.

Focus City in Sub-Saharan Africa: Nairobi, Kenya

This sub-section discusses the results of our analysis for Nairobi. Since our analytical parameters and assumptions have been sourced from the empirical literature, our primary data collection in Nairobi in May 2019, and a recent nationally representative study in Kenya (CCAK and MoE 2019), we expect that our results will be of special interest to policy-makers in this setting, with some transferability to other large cities in East Africa where a similar mix of fuels and cooking technology alternatives can be found. With sufficient work to obtain relevant data, the general framework can be applied in other locations as well.

The baseline distribution of stove and fuel use in Nairobi

Figure 1 shows the distribution of cooking fuels used in urban Kenya and Nairobi (CCAK and Kenya MoE 2019). As of late 2019, LPG formed the largest share of primary cooking fuels in Nairobi (56%), followed by kerosene (30%) and charcoal (6%).



Source: CCAK and Kenya MoE 2019

Figure 1. Primary cooking fuel distribution in urban Kenya and Nairobi

Based on these shares using different fuels (see Appendix D5 for more data), for Nairobi city, we estimate that almost 81 million hours every year are spent collecting fuel by the nearly 1 million households living in Nairobi (Table 6).[26] On a per household basis, this amounts to 82 hours spent yearly on fuel collection. This estimate is based on the fuel collection times recorded in our survey in Nairobi. Nairobi households are also estimated to spend 435 million hours cooking on a yearly basis. This equals approximately 442 hours per household per year. The amount of polluting fuel use is high: 26,502 tons of charcoal every year, and 82,543 tons of kerosene.

Turning to the health consequences of exposures to cooking-related pollution, the HAP-number of attributable cases of ALRI is estimated to be highest, at 496,468 cases per year. This high ALRI burden is consistent with the Global Burden of Disease Report's finding that lower respiratory infection is among the leading environmental risk factors for disease burden in Kenya (Naghavi et al. 2017). In our analysis, the second highest prevalence attributable to HAP is that of COPD (prevalence of 102,737), followed by stroke (prevalence of 19,667). The latter is the 10th leading cause of premature death in Kenya (IHME 2017). Lung cancer prevalence associated with cooking-related PM exposures is estimated at 73, since this health condition is less common. The relative differences in annual deaths attributable to HAP from the five diseases we include show a similar ranking: highest for ALRI (2,127), and lowest for lung cancer (31). On the environmental side, close to 1.06 million tons of CO_2 equivalents of cooking emissions are emitted per year in Nairobi. To put this number in perspective, in 2014, Kenya's CO_2 only emissions from solid fuel consumption were estimated to be 1.25 million tons (note that this number is highly sensitive to what is assumed about the renewability of firewood harvesting) and CO_2-only emissions from liquid fuel consumption were 10.25 million tons (World Bank 2018).[27]

---

[26] Fuel collection in urban areas refers exclusively to the commute time taken to purchase fuel, since households in Nairobi do not collect fuel from the local environment.

[27] Our calculations of CO_2-equivalent warming from stove-fuel combinations include additional climate-forcing agents beyond carbon dioxide. Specifically, we include methane, nitrous oxide, and other pollutants like black carbon, organic carbon and carbon monoxide.

Table 6. Baseline numbers for Nairobi households, and potential impacts of each transition assuming a complete shift

	Baseline	Traditional to Charcoal ICS	All Charcoal to LPG	Kerosene to LPG	All Charcoal to Ethanol	Kerosene to Ethanol
Number of households	985,016					
# Households affected by transition		44,776	54,274	292,550	54,274	292,550
Costs						
Time spent cooking ('000 hrs/yr)	435,241					
Time spent collecting fuel ('000 hrs/yr)	80,999					
Time spent learning new technology (total hrs)		1,208,962	1,465,408	7,898,843	1,465,408	7,898,843
Amount of charcoal fuel used (tons/yr)	26,502					
Amount of kerosene fuel used per month (tons/yr)	82,543					
People having COPD per yr	102,737					
Deaths from COPD per yr	107					
Cases of ALRI per yr	496,468					
Deaths from ALRI per yr	2,127					
Cases of IHD per yr	17,724					
Deaths from IHD per yr	623					
Cases of LC per yr	73					
Deaths from LC per yr	31					
Cases of stroke per yr	19,667					
Deaths from stroke per yr	1,383					
CO_2 equivalents of cooking emissions (million-tons/yr)	1.06					
Impacts of transition						
Charcoal fuel saved (tons/yr)		8,073	26,502	0	26,502	0
Kerosene fuel saved (tons/yr)		n.a.	n.a.	82,543	n.a.	82,543
Additional LPG or ethanol used (tons/yr)		n.a.	5,886	52,804	8,857	79,455
Cooking time saved ('000 hrs/yr)		4,900	4,752	0	4,752	0
Number of fewer COPD cases per yr		8	433	372	433	372
Number of fewer ALRI cases per yr		4	4,999	5,828	4,999	5,828
Number of fewer IHD cases per yr		0.0	34	36	34	36
Number of fewer LC cases per yr		0.0	0.30	0.27	0.30	0.27
Number of fewer Stroke cases per yr		0.19	29	51	29	51
Number of fewer COPD deaths per yr		0.01	0.45	0.39	0.45	0.39
Number of fewer ALRI deaths per yr		0.0	21	25	21	25
Number of fewer IHD deaths per yr		0.0	1.19	1.28	1.19	1.28
Number of fewer LC deaths per yr		0.0	0.13	0.11	0.13	0.11
Number of fewer Stroke deaths per yr		0.01	2	4	2	4
Carbon equivalent savings - all forcing (tons/yr)		90,317	169,420	15,336	169,420	15,336
Net biomass saved (tons/yr)		4,932	12,970	0	12,970	0

The potential of various fuel transition scenarios

Transition 1: Traditional charcoal stoves to charcoal ICS. This transition would affect nearly 45,000 households in Nairobi, who would move from traditional charcoal stoves to ICS. In a complete transition, over 1.2 million hours would be spent learning how to use charcoal ICS, compared with approximately 4.9 million cooking hours that would be saved on an annual basis due to improved cooking efficiency. Charcoal saved would exceed 8,000 tons. Because this transition would affect relatively few households and involve a less clean transition, once we account for exposure adjustment[28], we would actually expect very slight decreases in disease: 8 fewer cases of COPD and 4 fewer cases of ALRI, but no substantive changes in cases for the remaining three health conditions. No premature deaths would be avoided from this transition. Annual carbon-equivalent savings would be considerable, however, at nearly 90,317 tons and biomass use would decrease by over 4,900 tons per year of wood used in charcoal production.

Transition 2: All charcoal stoves to LPG. As previously discussed, this transition could theoretically affect all charcoal-using households in Nairobi (nearly 55,000). The number of hours that would be spent learning how to use LPG stoves are about 1.2 times those in transition 1 (1.5 million). On the impacts side, since this transition assumes a complete shift to LPG, the amount of charcoal that could be saved per year is the total amount of charcoal used for cooking in baseline technologies (over 26,500 tons). Transitioning households would now use 5,886 tons of new LPG every year. The yearly cooking time saving potential in this transition is fairly high (4.7 million hours). Annual carbon-equivalent savings (169,420 tons) and biomass savings (12,970 tons) are also among the highest of all the transitions. Compared to transition 1, fewer cases of diseases would be seen in this transition, with the highest cases avoided being for ALRI (4,999 cases per year). Approximately 25 deaths from all five health conditions per year could be avoided.

Transition 3: Kerosene to LPG. This transition would affect the largest number of households, since kerosene is the most widely used polluting fuel in Nairobi (estimated to be used by 292,550 households). Over 7.9 million hours would be spent learning use of LPG stoves. Every year, 82,543 tons of kerosene could be saved. Nearly 52,804 tons of additional LPG would be used every year. Owing to the transition from one non-biomass source to another, there would be no biomass savings, and yearly carbon-equivalent savings would be the limited, at 15,336 tons (mostly due to efficiency gains and lower emissions of non-CO_2 pollutants from kerosene combustion). Cases or prevalence of diseases avoided would be higher than other transitions for all health conditions, particularly for ALRI (5,828) and COPD (372). Likewise, mortality avoided would be highest from ALRI (25 deaths), while deaths avoided from other diseases would be under 6.

---

[28] The pollution exposure adjustment parameter accounts for the behavioral response that may reduce exposure reductions due to cleaner cooking, thereby increasing individuals' cooking time with harmful smoke. To elaborate further, we calculate the exposure adjustment for biomass-using technology (traditional stoves using firewood and charcoal) as follows: we first calculate the fraction of personal $PM_{2.5}$ exposure relative to kitchen $PM_{2.5}$ concentration in each study 'before' the transitional/clean technology was used (15 studies in total calculated both personal exposure and kitchen concentrations before and after transitional/clean technologies were used). We then average this fraction across the 15 studies, to get biomass-using technology exposure adjustment of 0.51. This number is used to calculate effective $PM_{2.5}$ for traditional biomass (firewood and charcoal). The exposure adjustment for transitional/clean technologies was calculated as follows: we first calculate the fraction of personal $PM_{2.5}$ exposure relative to kitchen $PM_{2.5}$ concentration in each study 'after' the transitional/clean technology was used and then average this fraction across the 15 studies, to get the transitional/clean technology exposure adjustment of 0.71. This number is used for all transitional and clean cooking technologies. In transitions from kerosene and LPG, this number is used for effective $PM_{2.5}$ calculations for kerosene and LPG as well as ethanol and electricity.

Transition 4: All charcoal stoves to ethanol. Since the number of charcoal users transitioning in this scenario would be equivalent to that in transition 2, and the emissions implications of ethanol use are comparable to those of LPG, the potential impacts are essentially the same. The only substantive difference would be that the additional clean fuel used would now be ethanol (8,857 tons per year) rather than LPG. The latter difference is driven by differing fuel efficiency and energy conversion of LPG and ethanol. While fewer cases of avoided diseases are seen in this transition, compared to transition 5, cases and deaths avoided would be higher than those seen in transitions 1 and 2 with the highest cases avoided being for ALRI (4,999 cases per year). Nearly 25 deaths per year could be avoided from the five health conditions included in our analysis.

Transition 5: Kerosene to ethanol. As the number of kerosene users transitioning in this scenario would be the same as that in transition 3, the impacts are again like those, barring the additional use of ethanol (79,455 tons per year). The cases or prevalence of diseases avoided would be identical to transition 3 (5,828 for ALRI and 372 for COPD). Likewise, mortality avoided would be highest from ALRI (25 deaths), while deaths from other diseases would be fall by 5 per year.

Net benefits of real-world policy interventions

Transition 1: Traditional charcoal stoves to charcoal ICS. We orient our analysis of policies to promote the transition from traditional charcoal to ICS around a 50% subsidy for the latter. (Recall that this subsidy also applies also in the other interventions, except for the ban on traditional technology). Among the non-ban interventions, subsidy costs and impacts are highest in the stove subsidy plus stove financing intervention, owing to the higher adoption rates achieved by that combination of instruments ($5,855/month) (Table 7). The stove ban has the highest program cost, however, due to the enforcement costs required to monitor the stove use of the nearly 45,000 households, who currently primarily use traditional charcoal technology ($63,433/month). In each of the four policy interventions, monthly operations and maintenance (O&M) and learning costs make up a smaller proportion of private costs, relative to the capital costs of acquiring new ICS. Importantly, the technology ban option imposes a net monthly cost of nearly $185,596 on households who would otherwise not transition to charcoal ICS due to their preferences for traditional technology.[29]

On the benefits side, the highest net present value of monthly time savings occurs under the technology ban option ($43,899), however, due to the much higher proportion of households transitioning, and the fact that stacking alongside traditional stoves is no longer allowed. This is followed by the stove subsidy plus stove financing policy intervention ($7,694/month), where adoption of ICS is second highest, but where technology stacking occurs. On monthly net fuel savings too, the polluting technology ban generates nearly six times higher benefits ($121,092/month) than the stove financing option ($21,224/month). As noted in the previous discussion of the potential of this transition, health benefits are actually modest for this transition, due to exposure adjustments – a behavioral response to cleaner technology. The highest private and social net health benefits are under the polluting technology ban intervention ($17,962 and $26,937, respectively). Similar to the time savings, fuel savings and health benefits, monthly net present value of carbon savings and ecosystem benefits from the technology ban

---

[29] Based on preferences measured in our Nairobi survey, as reflected in the demand curve for current technology.

are highest ($128,463 and $4,110, respectively). Climate mitigation and fuel savings generally represent the largest categories of benefits in this transition.

Table 7. Costs and benefits of Transition 1 under different policy interventions: Nairobi

	Stove subsidy	Fuel subsidy (w/ stove subsidy)	Stove financing (w/ stove subsidy)	BCC campaign (w/ stove subsidy)	Technology ban
Government subsidy costs					
Stove subsidy cost	$678	-	$5,855	$1,972	$0
Fuel subsidy	$0	-	$0	$0	$0
Program cost	$617	-	$5,326	$2,850	$63,433
Private costs					
Capital (stove) cost	$1,287	-	$12,223	$3,743	$71,292
Learning cost	$336	-	$2,897	$976	$7,933
O&M cost	$267	-	$2,303	$776	$6,306
Other net costs (ban-induced or for non-transitioning households)	$0	-	$0	$0	$185,596
Social costs					
Capital (stove) cost	$1,082	-	$9,692	$3,147	$22,642
Program cost	$617	-	$5,326	$2,850	$63,433
Learning cost	$105	-	$909	$306	$2,490
O&M cost	$267	-	$2,303	$776	$6,306
Other net costs (ban-induced or for non-transitioning households)	$0	-	$0	$0	$185,596
Private benefits					
Time savings	$891	-	$7,694	$2,592	$43,899
Net fuel savings	$2,459	-	$21,224	$7,150	$121,092
Private health benefits	$361	-	$3,115	$1,049	$17,962
Social benefits					
Time savings	$891	-	$7,694	$2,592	$43,899
Net fuel savings	$2,459	-	$21,224	$7,150	$121,092
Social health benefits	$541	-	$4,672	$1,574	$26,937
Carbon savings (Full)	$2,608		$22,515	$7,585	$128,463
Bio savings	$83		$720	$243	$4,110
Net Benefits (private)	**$1,821**	-	**$14,610**	**$5,296**	**($88,174)**
Net Benefits (social) Kyoto	**$2,512**	-	**$21,339**	**$6,251**	**($54,431)**
Net Benefits (social) Kyoto plus	**$4,512**	-	**$38,596**	**$12,065**	**$44,034**
Net Benefits (private w/o health)	**$1,460**	-	**$11,495**	**$4,247**	**($106,136)**

Adding these various costs and benefits together, we find that the stove financing policy intervention generates the greatest net private and social benefits among the four policy interventions: Accounting for all pollutants[30], the social net benefits (henceforth termed as social net benefits Kyoto plus) are $38,596 per month, and the private net benefits reach $11,495 per month. Also relevant, if households do not deem health benefits to be salient in their clean cooking energy decision-making, this policy combination still outperforms the others. Finally, it is worth noting that the less preferred policy options are inferior for different reasons: Both the stove subsidy only and subsidy plus BCC interventions do not achieve sufficient adoption and thus leave benefits on the table. The traditional charcoal stove ban, which

---

[30] We first calculate climate benefits including only three of the greenhouse gases mentioned in the Kyoto Protocol – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). We then calculate full climate benefits including three additional pollutants: black carbon (BC), organic carbon (OC), and carbon monoxide (CO).

performs nearly as well as the subsidy plus finance intervention in social terms (with $44,034/month of net benefits), is however by far the worst from a private household perspective, costing households $88,174/month on net. As such, there would likely lead to substantial resistance against this policy, as already witnessed in the past in Nairobi for a general charcoal use ban.

Of course, other subsidies may outperform the 50% starting point described above, so we also varied the ICS stove subsidy from 25% to 100% to show how this would affect the net present value (NPV) of (a) private benefits, (b) social benefits and (c) social benefits including all climate-forcing pollutants (Appendix A1). Stove subsidy levels below 50% generate no benefits and only minor costs, because adoption rates remain insignificant without more substantial subsidies. Note: This result is dependent on our model specification of the stove demand curve for which additional adoption requires prices to fall below about $15 per stove. As subsidies rise above 50%, then, adoption rises along with increased costs to the government, due to the larger subsidy delivered on each stove and the larger number of stoves being subsidized. Regardless, stove financing remains the most cost-beneficial policy intervention across subsidy levels, and the most beneficial subsidy level for social net benefits is about 75% (Figure 2, Transition 1).

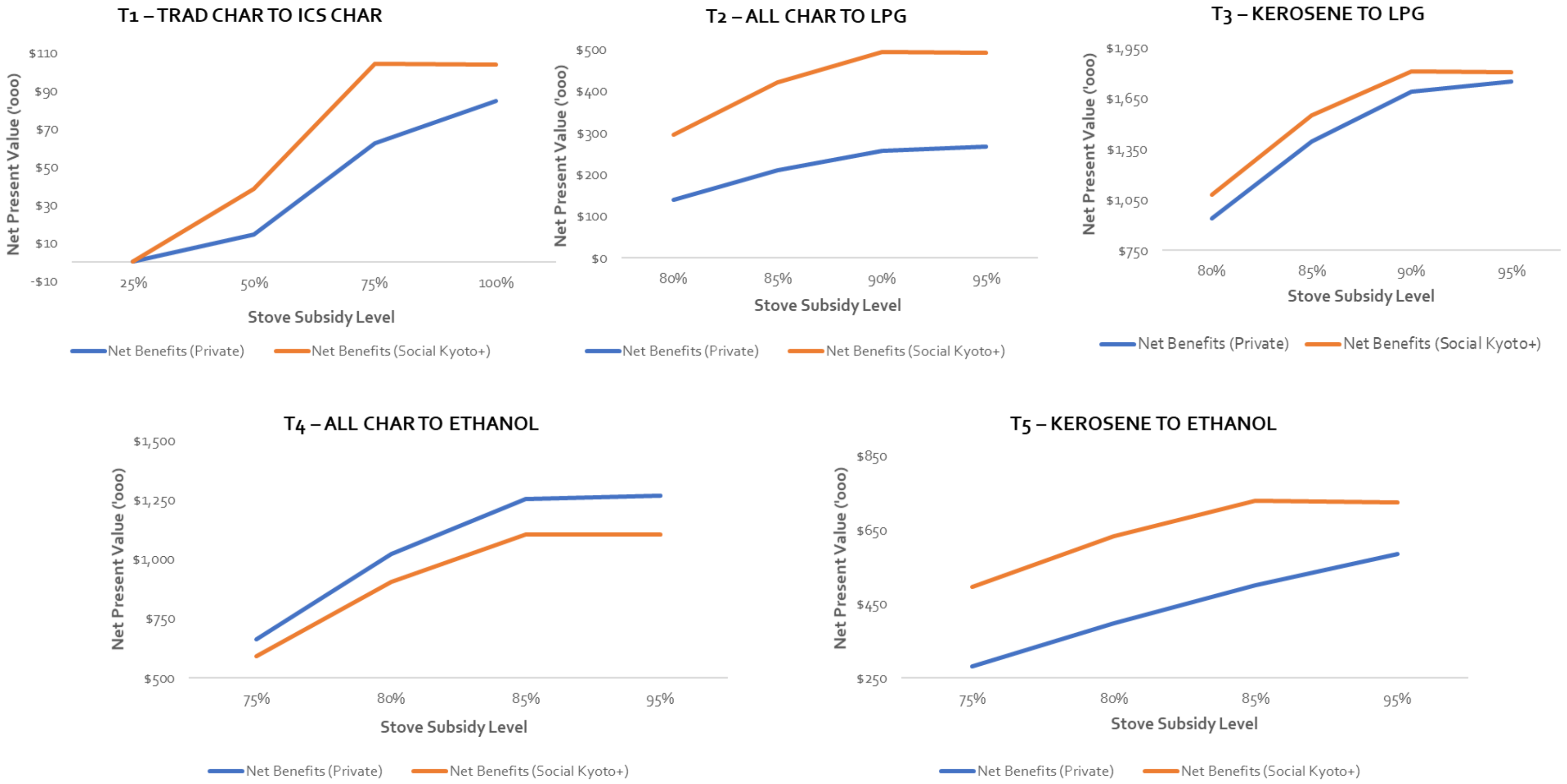


Figure 2. Net benefits at varying stove subsidy levels for most cost-beneficial policy choice in Nairobi: Stove financing plus stove subsidy policy intervention for transitions 1-3 and 5, and fuel subsidy plus stove subsidy for transition 4. Transition 1 (Traditional charcoal to Charcoal ICS), Transition 2 (All charcoal stoves to LPG), Transition 3 (Kerosene stoves to LPG), Transition 4 (All charcoal stoves to Ethanol) and Transition 5 (Kerosene stoves to Ethanol).

Transition 2: All charcoal users to LPG. For LPG, we initially set the stove subsidy at 85% (due to the higher cost of this stove and the need to more strongly reduce its price to observe increased adoption), and analyze a similar set of interventions, this time also including fuel subsidy as an additional policy instrument (Table 8). As in the analysis of the first transition, coupling a stove subsidy with other policy interventions leads to higher subsidy costs, as one would expect, with the highest in the stove financing case ($51,804/month). Subsidizing LPG fuel at 50% of the unit cost along with a stove subsidy, results in very large additional fuel subsidy costs of about $5.4 million per month for the government (these costs are high partly because this subsidy is assumed to flow to all users of LPG, and not just those newly adopting this technology). Similar to transition 1, a ban on any charcoal stoves (traditional or ICS) results in the highest program costs ($76,889/month), due to the enforcement costs that now apply to all charcoal users.

Since all potential households would transition under the ban, LPG-switching households would bear the largest stove and O&M costs ($169,616 and $10,286 per month, respectively). Combining stove financing with stove subsidy is the next costliest policy intervention in terms of these two costs, due to the higher number of new adopters under this policy combination. Across all five policy interventions, monthly learning costs are modest and range between $4,986 (stove subsidy only) and $9,384 (technology ban). The additional private costs under the technology ban, for households who would not ordinarily switch to LPG would be substantial at $1.1 million per month. The present value of monthly time savings ranges from $10,857 per month under the stove subsidy only option to $42,568 under the charcoal ban. Despite LPG fuel usage being lower than charcoal, due to LPG's higher price, monthly net fuel savings are negative for all interventions. Given the greater amount of transitioning under the ban, monthly private and social health benefits are highest under that policy ($1.7 million and $2.5 million, respectively), followed by the stove financing plus stove subsidy option ($409,907 and $611,713, respectively). Similar, monthly full climate benefits ($160,075) and ecosystem savings ($7,812) are greatest under the technology ban.

Despite having the highest time savings and health benefits of the five policy interventions, owing to high private costs, the private net benefits under the technology ban are negative (-$5,001/month), though social net benefits Kyoto plus are strongly positive ($1.1 million). There are three important points to note about this result. First, the fact that private net benefits would be negative, and by a very large amount if health benefits are not salient (this leads to a private net cost of U.S.$1.7 million per month) indicates that there could be substantial resistance to this type of intervention. Moreover, the distributional impacts on the affected population, poor households living primarily in slum areas, may be of particular concern. Second, our assumed yearly enforcement cost per household ($17) may understate actual enforcement costs. And finally, a polluting technology ban, especially for charcoal, may be politically challenging or infeasible to implement in Nairobi as the informal charcoal industry is a large employer in Kenya. In the absence of creating alternative opportunities for those employed in the charcoal sector, this policy intervention may have economic and social consequences not considered in our analysis.

Table 8. Costs and benefits of Transition 2 under different policy interventions: Nairobi

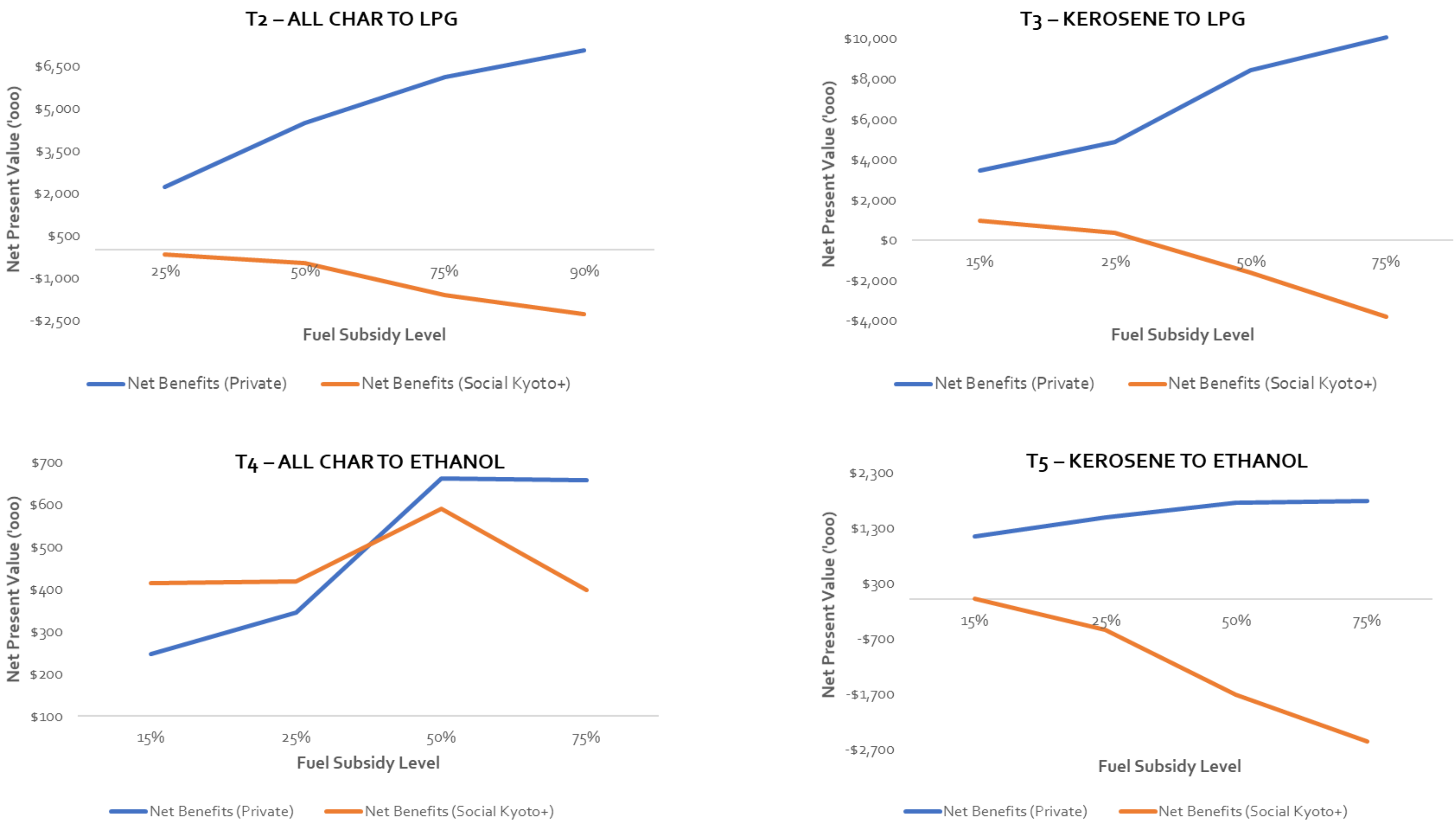
	Stove subsidy	Fuel subsidy (w/ stove subsidy)	Stove financing (w/ stove subsidy)	BCC campaign (w/ stove subsidy)	Technology ban
Government subsidy costs					
Stove subsidy cost	$32,225	$48,337	$51,804	$37,119	$0
Fuel subsidy	$0	$5,394,555	$0	$0	$0
Program cost	$8,434	$12,651.5	$13,559	$15,431	$76,889
Private costs					
Capital (stove) cost	$863	$1,294	$1,526	$994	$169,616
Learning cost	$4,986	$7,479	$8,016	$5,744	$9,384
O&M	$5,465	$8,198	$8,786	$6,296	$10,286
Other net costs (ban-induced or for non-transitioning households)	$0	($3,344,911)	$0	$0	$1,060,361
Social costs					
Capital (stove) cost	$32,474	$48,711	$52,245	$37,406	$48,987
Program cost	$8,434	$5,407,206	$13,559	$15,431	$76,889
Learning cost	$1,440	$2,160	$2,315	$1,659	$2,710
O&M cost	$5,465	$8,198	$8,786	$6,296	$10,286
Other net costs (ban-induced or for non-transitioning households)	$0	($3,344,911)	$0	$0	$1,060,361
Private benefits					
Time savings	$10,857	$32,571	$17,454	$12,506	$42,568
Net fuel savings	($123,958)	($120,415)	($199,274.5)	($142,787)	($486,023)
Private health benefits	$254,981	$1,232,030	$409,907	$293,713	$1,688,101
Social benefits					
Time savings	$10,857	$32,571	$17,454	$12,506	$42,568
Net fuel savings	($123,958)	($371,875)	($199,275)	($142,787)	($486,023)
Social health benefits	$380,514	$1,852,200	$611,713	$438,314	$2,543,987
Carbon savings (Full)	$40,827	$122,480	$65,633	$47,028	$160,075
Bio savings	$1,992	$5,977	$3,203	$2,295	$7,812
Net Benefits (private)	**$130,566**	**$4,472,124**	**$209,758**	**$150,398**	**($5,001)**
Net Benefits (social) Kyoto	**$243,132**	**($537,872)**	**$390,817**	**$274,348**	**$993,566**
Net Benefits (social) Kyoto plus	**$262,418**	**($480,012)**	**$421,822**	**$296,564**	**$1,069,186**
Net Benefits (private w/o health)	**($124,416)**	**$3,240,094**	**($200,149)**	**($143,314)**	**($1,693,102)**

The stove plus fuel subsidy intervention also has divergent net benefits: while private net benefits are the highest of all policy interventions ($4.5 million), social net benefits Kyoto plus are negative (-$480,012), driven by the high cost of providing subsidies to existing LPG users who do not need them, and negative net fuel savings for new users. This raises an important point about subsidies for clean fuels: They can be regressive in especially benefitting the rich, who have generally already transitioned, especially in urban areas. Unlike all other policy interventions, where private net benefits without health are negative, under this intervention private net benefits even excluding health gains are positive due to this subsidy transfer ($3.2 million). Of the remaining three interventions, the combined stove financing and stove subsidy policy option has the highest monthly private ($209,758) and social net benefits ($421,822), followed by the stove subsidy plus BCC policy (monthly private and social net benefits of $150,398 and $296,564).

Turning to alternative subsidy amounts, at the aforementioned rate of 85%, LPG stove adoption in the stove subsidy only intervention is 53.1%. On increasing the LPG stove subsidy to 95%, universal stove adoption can be achieved, but the relative proportions of costs and benefits remain similar as for the default stove subsidy level (Appendix A2). For the stove plus fuel subsidy intervention, the private net benefits continue to be positive for varying LPG fuel subsidy levels (between 25%-90%), but social net benefits increasingly become negative owing to increasing fuel subsidy costs imposed on the government (Figure 3). At all levels of LPG stove subsidies between 80%-90%, the private and social net benefits for the combined stove subsidy and stove financing option are positive (Appendix A2), rendering it the most consistently cost-beneficial policy intervention. In Figure 2 (Transition 2), we graphically show the private net benefits and the social net benefits for this intervention at varying stove subsidy levels.

Transition 3: Kerosene users to LPG. As with transition 2, we begin with a stove subsidy level of 85%, and note that stove subsidy costs to the government are again highest for the stove subsidy plus financing policy ($279,234/month) (Table 9). Fifty percent

LPG fuel subsidization alongside this stove subsidy, results in $8.4 million fuel subsidy costs to the government each month. Like transitions 1 and 2, a ban (in this transition, on kerosene stoves) results in the highest program costs ($414,445/month).



T2 – ALL CHAR TO LPG

T3 – KEROSENE TO LPG

T4 – ALL CHAR TO ETHANOL

T5 – KEROSENE TO ETHANOL

Figure 3. Net benefits at varying fuel subsidy levels for fuel subsidy plus stove subsidy policy intervention for Transitions 2-5 in Nairobi. Transition 2 (All charcoal stoves to LPG), Transition 3 (Kerosene stoves to LPG), Transition 4 (All charcoal stoves to Ethanol) and Transition 5 (Kerosene stoves to Ethanol).

Turning to private costs, LPG-switching households bear the highest monthly stove and learning costs under the technology ban ($0.98 million and $50,581, respectively). The combination of stove financing and stove subsidy is the second-most expensive policy intervention for households switching to LPG: monthly stove costs of $72,282 and learning costs of $43,206. Under the technology ban, the net cost to households in Nairobi that would otherwise not switch to LPG is over $4.9 million per month.

Table 9. Costs and benefits of Transition 3 under different policy interventions: Nairobi

	Stove subsidy	Fuel subsidy (w/ stove subsidy)	Stove financing (w/ stove subsidy)	BCC campaign (w/ stove subsidy)	Technology ban
Government subsidy costs					
Stove subsidy cost	$173,696	$260,545	$279,234	$200,081	$0
Fuel subsidy	$0	$8,401,041	$0	$0	$0
Program cost	$45,463	$68,194	$73,086	$83,174	$414,445
Private costs					
Capital (stove) cost	$40,875	$61,313	$72,282	$47,084	$982,435
Learning cost	$26,876	$40,314	$43,206	$30,959	$50,581
O&M	$23,446	$35,169	$37,692	$27,008	$44,126
Other net costs (ban-induced or for non-transitioning households)	$0	($3,344,911)	$0	$0	$4,919,655
Social costs					
Capital (stove) cost	$185,502	$278,252	$300,109	$213,679	$287,318
Program cost	$45,463	$8,469,236	$73,086	$83,174	$414,445
Learning cost	$7,762	$11,643	$12,478	$8,941	$14,608
O&M cost	$23,446	$35,169	$37,692	$27,008	$44,126
Other net costs (ban-induced or for non-transitioning households)	$0	($3,344,911)	$0	$0	$4,919,655
Private benefits					
Time savings	$0	$0	$0	$0	$0
Net fuel savings	$475,204	$3,681,395	$763,935	$547,387	$1,863,211
Private health benefits	$486,323	$1,542,504	$781,811	$560,195	$2,031,800
Social benefits					
Time savings	$0	$0	$0	$0	$0
Net fuel savings	$475,205	$1,425,611	$763,935	$547,387	$1,863,211
Social health benefits	$744,060	$2,369,239	$1,196,148	$857,082	$3,125,940
Carbon savings (Full)	$5,563	$16,690	$8,944	$6,408	$21,813
Bio savings	$0	$0	$0	$0	$0
Net Benefits (private)	**$870,329**	**$8,432,013**	**$1,392,566**	**$1,002,531**	**($2,101,787)**
Net Benefits (social) Kyoto	**$951,679**	**($1,670,776)**	**$1,528,017**	**$1,065,433**	**($712,223)**
Net Benefits (social) Kyoto plus	**$962,655**	**($1,637,850)**	**$1,545,661**	**$1,078,076**	**($669,190)**
Net Benefits (private w/o health)	**$384,006**	**$6,889,509**	**$610,756**	**$442,336**	**($4,133,587)**

This kerosene to LPG cooking transition does not yield time savings as the time efficiency of LPG stoves is similar to that for kerosene stoves, nor does it result in ecosystem benefits (since neither of these fuels contributes to forest loss in Kenya). The present value of private monthly fuel savings ranges from $475,204 under the stove subsidy only option to approximately $3.7 million under the stove subsidy plus fuel subsidy intervention. Monthly private and social health benefits are highest under the ban ($2 million and $.31 million, respectively), similar to transition 2. The fuel subsidy plus stove subsidy option, and the stove financing plus stove subsidy intervention, have high monthly private health ($1.5 million and $0.78 million, respectively) and social health ($2.4 million and $1.2 million, respectively) benefits. As with transition 2, full climate benefits in this transition are highest under the ban ($21,813).

In spite of having the highest fuel savings and health benefits of the five policy interventions, owing to its high costs, the net private and social benefits under the ban are negative (-$2.1 million and -$669,190, respectively). While the stove plus fuel subsidy intervention yields the highest private net benefits of all the policy instruments, its social net benefits are negative (-$1.6 million). The stove financing and BCC campaign options (in combination with stove subsidy) show positive private net benefits ($1.4 million and $1 million, respectively) and deliver the highest social net benefits ($1.5 million and $1.1 million, respectively).

At varying LPG stove subsidy levels (between 80%-95%), while no policy intervention yields both the highest net private and social benefits (i.e. stove plus fuel subsidy shows highest private net benefits, but stove financing plus stove subsidy shows highest social net benefits), the stove financing plus stove subsidy shows the highest positive benefits among the three policy interventions that have both positive net private and social returns. Thus, this intervention appears to be the most consistently cost-beneficial policy intervention for accelerating a transition from kerosene to LPG (see also Appendix A3). Varying levels of LPG fuel subsidy (between 15%-75%) yields increasingly positive private net benefits (Figure 3, Transition 3), but at the cost of declining social net benefits. Figure 2 (Transition 3) shows the positive net benefits (private and social Kyoto plus) under varying stove subsidy levels for the stove financing intervention – the most cost-beneficial policy option for supporting this transition.

<u>Transition 4: All charcoal users to ethanol</u>. The relative costs in this transition are largely similar to those in transition 2 (Table 10), so we do not comment on them in detail here. We note just a few differences: First, in the short term, the fuel subsidy costs to the government ($328,565/month) from 50% subsidization of ethanol would be much lower than the fuel subsidy costs to the government in transition 2, because there are currently no primary ethanol users in Nairobi to whom these subsidies would also be granted, whereas 56% of the city uses LPG as primary cooking fuel. Of course, long-term ethanol subsidies would likely induce households to switch from LPG to ethanol, thereby significantly increasing these subsidy costs over time.

Table 10. Costs and benefits of Transition 4 under different policy interventions: Nairobi

	Stove subsidy	Fuel subsidy (w/ stove subsidy)	Stove financing (w/ stove subsidy)	BCC campaign (w/ stove subsidy)	Technology ban
Government subsidy costs					
Stove subsidy cost	$14,164	$21,247	$27,034	$17,382	$0
Fuel subsidy	$0	$328,565	$0	$0	$0
Program cost	$5,708	$8,562	$10,894	$11,124	$76,889
Private costs					
Capital (stove) cost	$2,999	$4,498	$6,296	$3,680	$117,823
Learning cost	$3,343	$5,014	$6,380	$4,102	$9,407
O&M cost	$3,655	$5,482	$6,976	$4,485	$10,286
Other net costs (ban-induced or for non-transitioning households)	$0	$0	$0	$0	$838,971
Social costs					
Capital (stove) cost	$15,039	$22,558	$28,870	$18,455	$34,351
Program cost	$5,708	$337,126	$10,894	$11,124	$76,889
Learning cost	$975	$1,462	$1,860	$1,196	$2,743
O&M cost	$3,655	$5,482	$6,976	$4,485	$10,286
Other net costs (ban-induced or for non-transitioning households)	$0	$0	$0	$0	$838,971
Private benefits					
Time savings	$7,260	$21,781	$13,857	$8,910	$42,568
Net fuel savings	($129,485)	($169,412)	($247,132)	($158,897)	($759,183)

Private health benefits	$170,515	$823,372	$325,441	$209,247	$1,688,101
Social benefits					
Time savings	$7,260	$21,781	$13,857	$8,910	$42,568
Net fuel savings	($129,485)	($388,455)	($247,132)	($158,897)	($759,183)
Social health benefits	$254,464	$1,237,466	$485,662	$312,263	$2,543,987
Carbon savings (Full)	$27,302	$81,907	$52,108	$33,504	$160,075
Bio savings	$1,074	$3,223	$2,050	$1,318	$6,299
Net Benefits (private)	**$38,294**	**$660,746**	**$72,515**	**$49,993**	**($5,001)**
Net Benefits (social) Kyoto	**$122,342**	**$550,600**	**$233,331**	**$146,011**	**$954,887**
Net Benefits (social) Kyoto plus	**$135,240**	**$589,293**	**$257,948**	**$161,838**	**$1,030,507**
Net Benefits (private w/o health)	**($132,221)**	**($162,625)**	**($252,926)**	**($162,254)**	**($1,693,102)**

Turning to differences in benefits relative to transition 2, like LPG, though ethanol usage is lower than charcoal, all policy interventions have negative monthly net fuel savings due to the fuel's higher price. And thus, as in transition 2, on calculating net benefits, as with the charcoal to LPG transition, the ban does not yield positive private net benefits (-$5,001/month) but has strongly positive social net benefits ($1 million/month). The stove plus fuel subsidy intervention again delivers the greatest private net benefits ($660,746/month), driven mainly by private fuel cost reductions and private health benefits; private net benefits without health are negative for all policies. In terms of social net benefits, stove financing ($257,948/month) is third best after the ban and stove plus fuel subsidy policies.

Assuming a 75% default stove subsidy, ethanol stove adoption in the stove subsidy only intervention would reach about 36%. At ethanol stove subsidy levels of 92%, all households would adopt this solution, and the total costs and benefits would increase, but the relative proportions remain similar to that under the 75% stove subsidy (Appendix A4). On varying ethanol stove subsidy levels between 75%-95%, the private net benefits and social net benefits Kyoto plus would both remain positive for stove financing, rendering it the most cost-beneficial policy choice (Figure 2, Transition 4). For the stove plus fuel subsidy intervention, at fuel subsidy levels above 50%, the private net benefits remain fairly constant, but social net benefits drop steadily owing to increasing costs imposed on the government (Figure 3, Transition 4). Social net benefits see a sharp drop between the 50%-75% ethanol fuel subsidy levels.

<u>Transition 5: Kerosene users to ethanol</u>. Just as the metrics for transitions 2 and 4 exhibit many similarities, so do the relative costs and benefits of this transition mirror those of transition 3 (Table 11). We again focus primarily on key differences. Subsidizing ethanol by half the unit price along with a 75% default stove subsidy, results in $2.9 million fuel subsidy costs to the government. Meanwhile, the net present value of private monthly fuel savings is positive only for the combined fuel and stove subsidy option ($0.8 million). Relative to transition 3, full climate benefits are lower in transitioning from kerosene to ethanol owing to low calorific value of ethanol compared to LPG.

Thus, the private net benefits are highest under the stove plus fuel subsidy option ($1.8 million/month) while social net benefits Kyoto plus are highest under the stove financing option ($496,497/month). A BCC campaign plus stove subsidy again somewhat outperforms a stove subsidy only option.

On varying ethanol stove subsidy levels between 80-95%, similar to LPG stove subsidy variations in transition 3, we find that the highest private net benefits and social net benefits occur with stove financing (Appendix A5). Ethanol fuel subsidy variations yield positive private net benefits at all levels, similar to what we observed in transition 4 (Figure 3). However, social net benefits decline with increasing ethanol fuel subsidies and turn negative at fuel subsidy levels higher than 15%. Finally, we observe that net benefits (private and social) are positive for the stove financing option making it the most cost-beneficial policy intervention in this transition (Figure 2, Transition 5).

Table 11. Costs and benefits of Transition 5 under different policy interventions: Nairobi

	Stove subsidy	Fuel subsidy (w/ stove subsidy)	Stove financing (w/ stove subsidy)	BCC campaign (w/ stove subsidy)	Technology ban
Government subsidy costs					
Stove subsidy cost	$76,350	$114,524	$145,719	$93,692	$0
Fuel subsidy	$0	$2,947,481	$0	$0	$0
Program cost	$30,766	$46,149	$58,719	$59,963	$414,445
Private costs					
Capital (stove) Cost: Ethanol switchers	$40,388	$60,583	$84,793	$49,562	$703,263
Learning cost	$18,017	$27,026	$34,387	$22,110	$50,705
O&M cost	$15,679	$23,519	$29,925	$19,241	$44,126
Other net costs (ban-induced or for non-transitioning households)	$0	$0	$0	$0	$2,748,246
Social costs					
Capital (stove) Cost	$88,125	$132,187	$170,440	$108,142	$208,842
Program cost	$30,766	$2,993,630	$58,719	$59,963	$414,445
Learning cost	$5,253	$7,879	$10,025	$6,446	$14,783
O&M cost	$15,679	$23,519	$29,925	$19,241	$44,126
Other net costs (ban-induced or for non-transitioning households)	$0	$0	$0	$0	$2,748,246
Private benefits					
Time savings	$0	$0	$0	$0	$0
Net fuel savings	($100,160)	$832,254	($191,162)	($122,910)	($587,247)
Private health benefits	$325,222	$1,031,529	$620,709	$399,094	$2,031,800
Social benefits					
Time savings	$0	$0	$0	$0	$0
Net fuel savings	($100,160)	($150,240)	($191,162)	($122,910)	($587,247)
Social health benefits	$497,580	$1,584,397	$949,667	$610,602	$3,125,940
Carbon savings (Full)	$3,720	$11,161	$7,101	$4,565	$21,813
Bio savings	$0	$0	$0	$0	$0
Net Benefits (private)	**$150,977**	**$1,752,655**	**$280,442**	**$185,271**	**($2,101,787)**
Net Benefits (social) Kyoto	**$253,978**	**($1,733,916)**	**$482,489**	**$289,459**	**($912,970)**
Net Benefits (social) Kyoto plus	**$261,318**	**($1,711,897)**	**$496,497**	**$298,466**	**($869,937)**
Net Benefits (private w/o health)	**($174,245)**	**$721,126**	**($340,267)**	**($213,823)**	**($4,133,587)**

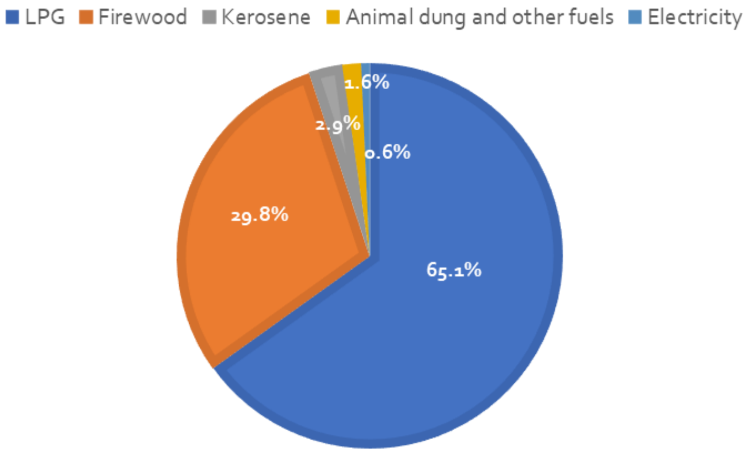
Focus City in South Asia: Kathmandu, Nepal

This sub-section shifts the focus to the second urban case, the Kathmandu Valley of Nepal. Again, since our analytical parameters and assumptions have been sourced from the empirical literature, our primary data collection in peri-urban areas of the valley in July-August 2019, and a nationally representative dataset from Nepal, we expect that our results will be of special interest to policy-makers in this setting. We utilize the same general framework as was applied for the Nairobi case study, to analyze the relevant set of transitions for this context.

The baseline distribution of stove and fuel use in Kathmandu Valley

We first present the fuel use shares for urban Nepal, drawing on data from the urban Kathmandu Valley (districts of Kathmandu, Lalitpur and Bhaktapur) in the Nepal Census (2011), and urban Nepal's use of primary cooking fuels as indicated in the Demographic and Health Survey (2016).[31] LPG forms the largest share of cooking fuels (65%), then firewood (30%), followed by kerosene (3%) and finally electricity (less than 1%) (Figure 4). With recent LPG supply-related challenges and policy changes around electricity, stakeholders interviewed in our consultative meetings noted that these cooking fuel shares are changing, so our assumptions may not be fully accurate. Along with the expected increase in electricity use for cooking, LPG and firewood use are anticipated to decline, though many expect incomplete fuel switching from solid to clean fuels and increased stacking of multiple clean options. Our analysis relies on our survey data to specify the primary cooking fuel distribution, as the percentages fall within the range of values from the Nepal Census (2011) and DHS Survey (2016). Specifically, our survey found that 84.3% of peri-urban Kathmandu Valley households primarily use LPG, followed by 11.4% that use firewood as their primary cooking fuel[32]. Since there were no primary electric stove users in our study sample, we apply the value – probably an underestimate – from the 2011 Census: 0.1%.

Based on the relevant data parameters (see Table D5 for more data), we estimate that more than 89.3 million hours every year are spent collecting wood fuel in the urban Kathmandu Valley, where 614,777 households reside (Table 12). This amounts to 145.3 hours spent on fuel collection every year, per household. This calculation assumes that firewood collection time is 1.1 hours, that LPG collection time is 0.3 hours, and that electricity does not require collection. Households in the Kathmandu Valley are further estimated to spend over 417.5 million hours per year cooking. In per household terms, this amounts to 679 hours spent cooking yearly. Use of firewood, the main polluting fuel in the urban Kathmandu Valley market, is estimated at 28,210 tons every year.



Source: Nepal National Population and Housing Census 2011, DHS 2016

Figure 4. Primary cooking fuel distribution in urban Nepal[33]

---

[31] Details of this input parameter are in Appendix D, Table D5. Since there are no rural-urban disaggregated data by district in DHS (2016), we use the average numbers for urban Nepal. The average fuel shares thus calculated are more than the latest Nepal Census (2011) but less than the latest DHS (2016) data.

[32] Of the main firewood users in our sample, 90% collected firewood while the remaining 10% purchased it. The majority of primary LPG-using households in our sample (75%) picked up LPG cylinders from retailers; for the remaining 25% households, LPG cylinders were delivered.

[33] The fuel shares used in this figure are average values from the Nepal Census 2011 (data for the urban districts of Kathmandu, Lalitpur and Bhaktapur that together form Kathmandu Valley) and DHS 2016 (data for urban Nepal only). In discussions with various clean cooking

In considering the health consequences of cooking-related pollution exposures, the number of COPD cases is estimated to exceed 106,000 cases per year. IHD cases have the second highest prevalence at 32,766 cases per year, followed by stroke (17,423) and ALRI (2,414). As the prevalence of lung cancer is least common of these five health conditions, our estimates reflect the same-213 cases per year. The yearly deaths from these health conditions is slightly different from their relative prevalence: highest for IHD (2,666), followed by COPD (1,594) and stroke (1,225). This highest number of deaths from IHD is aligned with the Global Burden of Disease Report's findings for Nepal that IHD is the second leading cause of death, followed by ALRI (3rd), COPD (4th) and stroke (6th) (Naghavi et al. 2017).

---

stakeholders in Kathmandu, we understand that these numbers are likely to change, particularly increase in electricity use (following the trade blockade in 2015, and reliable and regular electricity supply in subsequent years), slight reduction in LPG use (also following the trade blockade in 2015 and uncertainties around LPG supply) and reduction in firewood use (since clean fuels like LPG and electricity are widely available).

Table 12. Baseline numbers for Kathmandu households, and potential impacts of each transition assuming a complete shift

	Baseline	Traditional Firewood to Natural Draft ICS	Traditional Firewood to LPG Stove	Traditional Firewood to Electric Stove	LPG to Electric Stove	Electric to LPG Stove
Number of households	614,777					
# Households affected by transition		70,208	70,208	70,208	518,073	615
Costs						
Time spent cooking ('000 hours/year)	417,477					
Time spent collecting fuel ('000 hours/year)	89,349					
Time spent learning new technology (total hours)		1,930,707	1,930,707	1,930,707	0	0
Amount of firewood fuel used (tons/year)	28,210					
Amount of LPG fuel used (tons/year)	97,197					
Amount of electricity used (kWh/year)	686					
Cases of COPD per year	106,621					
Deaths from COPD per year	1,594					
Cases of ALRI per year	2,414					
Deaths from ALRI per year	430					
Cases of IHD per year	32,766					
Deaths from IHD per year	2,666					
Cases of LC per year	213					
Deaths from LC per year	205					
Cases of Stroke per year	17,423					
Deaths from Stroke per year	1,225					
CO_2-eq. of cooking emissions (million-tons/year)	0.59					
Impacts of transition						
Firewood fuel saved (tons/year)		4,582	28,210	28,210	n.a.	n.a.
LPG fuel saved (tons/year)		n.a.	0	n.a.	97,197	0
Electricity saved (kWh/year)		n.a.	n.a.	0	0	686
Additional LPG used (tons/year)		n.a.	8,782	n.a.	n.a.	115
Additional Electricity used (kWh/year)		n.a.	n.a.	106,448	577,927	n.a.
Cooking time saved ('000 hours/year)		11,477	12,081	6,645	0	0
Number of fewer COPD cases per year		992	1,572	1,587	116	(0.1)
Number of fewer ALRI cases per year		13	35	36	6	(0.0)
Number of fewer IHD cases per year		79	143	145	15	(0.0)
Number of fewer LC cases per year		2	2.8	2.8	0.2	(0.0)
Number of fewer Stroke cases per year		11	25.3	25.9	4.8	(0.0)
Number of fewer COPD deaths per year		15	23.5	23.7	1.7	(0.0)
Number of fewer ALRI deaths per year		2	6.2	6.3	1.1	(0.0)
Number of fewer IHD deaths per year		6	11.7	11.8	1.2	(0.0)
Number of fewer LC deaths per year		2	2.7	2.7	0.2	(0.0)
Number of fewer Stroke deaths per year		1	1.8	1.8	0.3	(0.0)
Carbon equivalent savings - all forcing (tons/year)		15,853	24,057	70,818	517,514	(614)

Net biomass saved (tons/year)		202	1,241	1,241	0	0

Turning to the environmental indicators, approximately 0.59 million-tons of CO_2 equivalents of cooking emissions are emitted per year in Kathmandu Valley. Putting this number in context and again subject to assumptions about the renewability of biomass harvesting, in 2014, Nepal's CO_2-only emissions from solid fuel consumption were 1.83 million-tons and CO_2-only emissions from all fossil fuels – for provision of various energy services including household use – were 4.65 million-tons (World Bank 2018).

The potential of various fuel transition scenarios

Transition 1: Traditional firewood stove users to natural draft ICS. This transition would affect the just over 70,000 Kathmandu Valley households using traditional firewood stoves, moving them to natural draft ICS. Over 1.9 million hours are estimated to be required for learning to use the ICS, compared with approximately 11.5 million cooking hours saved on an annual basis from improved cooking efficiency. As expected, firewood saved would be relatively limited (compared to full transitions to LPG and electricity, for example) at 4,582 tons. The maximum number of cases avoided of disease – for a universal shift from traditional stoves to biomass ICS – would similarly be lower than in transitions 2 and 3: 992 fewer cases of COPD, 79 fewer cases of IHD, 11 fewer cases of stroke and 15 fewer cases of ALRI and lung cancer combined. The annual number of deaths avoided from this complete transition would thus come to about 26. CO_2-equivalent savings would reach 15,853 tons per year and biomass use reduction would be 202 tons per year; these values would be roughly one-fifth those of the maximum potential savings in transitions 2 and 3.

Transition 2: Traditional firewood stove users to LPG. This transition would affect the same number of households considered in transition 1, who would instead move to LPG. Similar to transition 1, we estimate over 1.9 million hours to be spent learning how to use LPG stoves, compared with a potential of approximately 12.1 million cooking hours saved on an annual basis. The yearly cooking time saving potential in this transition is highest among the five scenarios. Meanwhile, the firewood saved could reach about 28,210 tons with a full transition to LPG, while close to 8,782 tons of LPG would be used. The second-highest number of reduced health conditions would be seen from this transition: 1,572 fewer cases of COPD, 143 fewer cases of IHD, 35 fewer cases of ALRI, and less than 30 fewer cases of stroke and lung cancer together. The annual number of deaths avoided from this transition would be just under 50, with the greatest mortality reduction for COPD. Potential carbon-equivalent savings would be about 24,057 tons per year and biomass use reduction could reach 1,241 tons per year.

Transition 3: Traditional firewood stove users shifting to electricity. The number of Kathmandu Valley households affected by this transition would again be the same (70,208) as in transitions 1 and 2. Similar to transition 2, the potential amount of firewood saved would be 28,210 tons per year, and learning hours would again be the same, at 1.9 million hours. Approximately 6.6 million cooking hours would be saved under a complete transition to electric cooking, and 106,448 kWh/yr of electricity would be consumed.[34] The yearly potential for cases avoided of disease in the current transition 3 is the highest of all five transitions: 1,587 fewer cases of COPD, 145 fewer cases of IHD and 36 fewer cases of ALRI. Stroke and lung cancer cases avoided combined would be under 30. The yearly number of deaths avoided from all five health conditions combined would be similar to those in transition 2, with the highest number of deaths averted from COPD (24 deaths). CO_2-equivalent savings potential is the second-highest in this

---

[34] Note that the conversion factors for electricity assume the use of electric induction stoves, which have very high thermal efficiency. Specifically, we assume that 1 hour of use of such technology requires 1.98 kW of electricity, which is consistent with most of the options available in the Nepal market, and use the relative time efficiency of induction stoves (relative to the transitioning technology) to determine the cooking time required.

transition at 70,818 tons per year, and biomass use reduction could reach 1,241 tons per year, as in transition 2.

Transition 4: LPG users to electricity. This transition would affect the largest number of households, since LPG is the most widely used fuel in Kathmandu Valley (518,073). We assume that no time would be spent learning how to use electric stoves since LPG and electric stoves are advanced and similar cooking technologies. While about 97,197 tons of LPG would be saved, about 577,927 kWh per year of electricity would instead be used under this complete transition. Health impacts would be limited: At most 116 fewer cases of COPD, plus 26 fewer cases from the remaining four health conditions each year. The total number of deaths averted from this transition, for all five health conditions considered, would at most reach 5 per year. Potential CO_2-equivalent savings would be the highest of all transitions at 517,514 tons each year, and since the transition is from a non-biomass fuel to another, there would be no biomass use reductions.

Transition 5: Electric cooking users shifting to LPG. Of the five transition scenarios, this transition has the fewest potential number of affected households, due to the low number of electricity users for cooking in Kathmandu (615). While 686 kWh of electricity could be saved, about 115 tons of LPG would replace those savings. The health consequences of this shift – even if it were complete – would be close to nil. In this scenario, approximately 614 tons of emissions potential could result per year. As in transition 4, there would be no biomass use reductions.

Net benefits of fuel transition scenarios under different policy interventions

Transition 1: Traditional firewood stove users to ICS (natural draft). To begin our policy analysis, we again begin with a 50% subsidy for a natural draft firewood ICS, also applied alongside all other policy interventions except for the traditional firewood stove ban. Due to the higher adoption rate of the stove subsidy plus stove financing intervention (68.8%), it has the highest monthly subsidy costs ($17,055) of all other interventions (Table 13). Enforcement costs necessary to eliminate use of traditional biomass stoves among the 70,208 households would cost nearly $100,000 per month. In policy interventions involving the stove subsidy, monthly capital costs of acquiring the ICS would be the largest private cost item, especially in the stove subsidy plus stove financing intervention ($59,405/month). The ban on traditional firewood stoves, however, would also impose a large monthly net cost of $486,295 on households that would ordinarily not transition to the ICS owing to their preference for traditional cooking methods (as measured in our survey in Kathmandu Valley).

Turning to the benefits of this transition, the net present value of monthly time savings would be highest under the ban ($193,296), as all households would transition completely to the ICS under this intervention. The next highest time savings would occur with stove subsidy plus financing ($63,825/month), due to the higher adoption rate under that policy relative to the others. Monthly net fuel savings follow a similar pattern: highest for the ban ($87,828/month), followed by the stove subsidy plus stove financing intervention ($29,000/month). For monthly health benefits, the technology ban intervention would yield the highest positive benefits ($110,085 private and $241,021 social benefits each month). Similar to time savings, fuel savings and health benefits, the monthly net present value of carbon savings and ecosystem benefits under the ban would be highest ($23,168 and $2,016, respectively).

However, on calculating total monthly net benefits (private and social), though banning traditional firewood stove use yields maximum time, fuel and health benefits, owing to the high cost to households currently using traditional firewood stoves, net benefits become negative. Though private net benefits are highest under the stove subsidy plus BCC intervention ($25,780), the social net benefits are highest for stove subsidy plus financing ($74,761).

Table 13. Costs and benefits of Transition 1 under different policy interventions: Kathmandu Valley

	Stove subsidy	Fuel subsidy (w/ stove subsidy)	Stove financing (w/ stove subsidy)	BCC campaign (w/ stove subsidy)	Technology ban
Government subsidy costs					
Stove subsidy cost	$9,051	-	$17,055	$11,052	$0
Fuel subsidy	$0	-	$0	$0	$0
Program cost	$11,054	-	$20,830	$21,438	$99,461
Private costs					
Capital (stove) cost	$21,301	-	$59,405	$26,010	$116,697
Learning cost	$10,632	-	$20,035	$12,982	$29,123
O&M cost	$10,060	-	$18,956	$12,284	$27,556
Other net costs (ban-induced or for non-transitioning households)	$0	-	$0	$0	$486,295
Social costs					
Capital (stove) cost	$16,291	-	$37,247	$19,893	$39,668
Program cost	$11,054	-	$20,830	$21,438	$99,461
Learning cost	$3,614	-	$6,810	$4,414	$9,900
O&M cost	$10,060	-	$18,956	$12,284	$27,556
Other net costs (ban-induced or for non-transitioning households)	$0	-	$0	$0	$486,295
Private benefits					
Time savings	$33,871	-	$63,825	$41,359	$193,296
Net fuel savings	$15,390	-	$29,000	$18,792	$87,828
Private health benefits	$13,843	-	$26,086	$16,904	$110,085
Social benefits					
Time savings	$33,871	-	$63,825	$41,359	$193,296
Net fuel savings	$15,390	-	$29,000	$18,792	$87,828
Social health benefits	$30,495	-	$57,464	$37,237	$241,021
Carbon savings (Full)	$4,060	-	$7,650	$4,957	$23,168
Bio savings	$353	-	$666	$431	$2,016
Net Benefits (private)	**$21,112**	-	**$20,516**	**$25,780**	**($268,464)**
Net Benefits (social) Kyoto	**$38,558**	-	**$66,107**	**$39,142**	**($141,759)**
Net Benefits (social) Kyoto plus	**$43,150**	-	**$74,761**	**$44,750**	**($115,550)**
Net Benefits (private w/o health)	**$7,269**	-	**($5,570)**	**$8,876**	**($378,549)**

In Appendix A6, we show the present value of the (a) private, (b) social, and (c) social plus net benefits, where the latter includes all climate-forcing pollutants, as a function of the ICS subsidy. At stove subsidy levels below 25%, net benefits are nil due to lack of adoption of the ICS (private or social). With increasing levels of stove subsidy, net benefits increase accordingly for all interventions. The stove financing and stove subsidy intervention has the highest social net benefits at all stove subsidy levels, making it the most cost-beneficial policy intervention for supporting this transition (Figure 5, Transition 1).

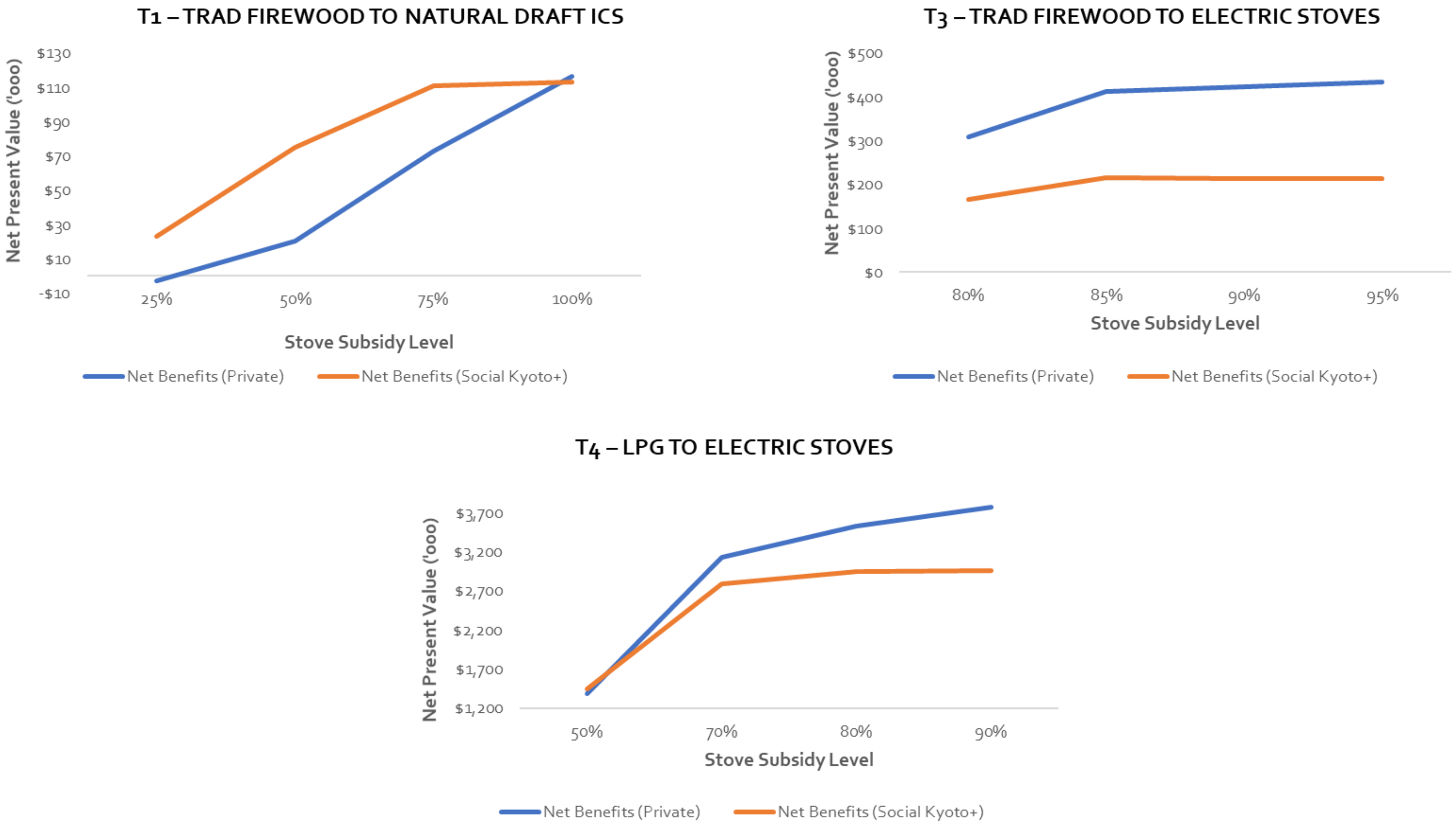


Figure 5. Net benefits at varying stove subsidy levels for most cost-beneficial policy choice in Kathmandu Valley: Stove financing plus stove subsidy policy intervention for transitions 1 and 4, and fuel subsidy plus stove subsidy for transition 3. Transition 1 (Traditional firewood stoves to natural draft ICS), Transition 3 (Traditional firewood stoves to electric stoves) and Transition 4 (LPG stoves to Electric stoves). Transitions 2 (Traditional firewood stoves to LPG) and 5 (Electric stoves to LPG) are excluded from this graph as social net benefits are negative under all policy options.

Transition 2: Traditional firewood stove users to LPG: We set the LPG stove subsidy at 50%, lower than in Kenya owing to the lower LPG stove cost in Nepal, and assessed the same interventions described in the first transition, along with a fuel subsidy (Table 14). As LPG stove adoption is highest under the stove financing intervention, the monthly stove subsidy costs are also greatest ($11,302). The combination of a 50% LPG fuel and stove subsidy, results in a fuel subsidy cost of $4 million/month to the government. As in transition 1, a ban on traditional firewood stoves results in the highest monthly program costs ($99,461/month).

Table 14. Costs and benefits of Transition 2 under different policy interventions: Kathmandu Valley

	Stove subsidy	Fuel subsidy (w/ stove subsidy)	Stove financing (w/ stove subsidy)	BCC campaign (w/ stove subsidy)	Technology ban
Government subsidy costs					
Stove subsidy cost	$6,630	$9,945	$11,302	$7,798	$0
Fuel subsidy	$0	$4,015,362	$0	$0	$0
Program cost	$8,985	$13,477	$15,317	$16,784	$99,461
Private costs					
Capital (stove) cost	$21,804	$32,706	$55,011	$25,645	$95,188
Learning cost	$12,076	$18,114	$20,586	$14,203	$26,359
O&M	$6,888	$10,333	$11,743	$8,102	$15,036
Other net costs (ban-induced or for non-transitioning households)	$0	($2,457,232)	$0	$0	$185,192
Social costs					
Capital (stove) cost	$11,933	$17,900	$24,683	$14,036	$23,154
Program cost	$8,985	$4,028,839	$15,317	$16,784	$99,461
Learning cost	$2,937	$4,406	$5,007	$3,455	$6,412
O&M cost	$6,888	$10,333	$11,743	$8,102	$15,036
Other net costs (ban-induced or for non-transitioning households)	$0	($2,457,232)	$0	$0	$185,192
Private benefits					
Time savings	$44,743	$134,228	$76,273	$52,625	$203,469
Net fuel savings	($75,834)	($7,827)	($129,276)	($89,195)	($344,861)
Private health benefits	$23,921	$119,296	$40,778	$28,135	$194,704
Social benefits					
Time savings	$44,743	$134,228	$76,273	$52,625	$203,469
Net fuel savings	($75,834)	($7,827)	($129,276)	($89,195)	($344,861)
Social health benefits	$52,641	$259,593	$89,738	$61,915	$423,032
Carbon savings (Full)	$7,732	$23,195	$13,180	$9,094	$35,160
Bio savings	$2,729	$8,188	$4,653	$3,210	$12,412
Net Benefits (private)	**($47,939)**	**$2,641,776**	**($99,564)**	**($56,385)**	**($268,464)**
Net Benefits (social) Kyoto	**(10,372)**	**$(1,221,785)**	**$(22,021)**	**$(18,416)**	**$(52,968)**
Net Benefits (social) Kyoto plus	**$1,266**	**$(1,186,870)**	**$(2,182)**	**$(4,727)**	**$(43)**
Net Benefits (private w/o health)	**($71,860)**	**$2,522,480**	**($140,342)**	**($84,520)**	**($463,168)**

Households transitioning to LPG bear the highest monthly capital (stove) cost under the polluting technology option ($95,188), followed by the stove subsidy plus stove financing option ($55,011). Monthly learning and O&M costs are highest for the ban ($26,359 and $15,036, respectively) followed by stove financing ($20,586 and 11,743, respectively). Under the ban policy, households that would not switch to LPG under normal circumstances would incur an additional net monthly cost of $185,192.

On examining the benefits, consistent with the higher adoption under the ban, we find that this policy would generate the greatest monthly time savings ($203,469), followed by the stove plus fuel subsidy option ($134,228). Monthly fuel savings across all interventions would be negative, despite LPG fuel usage being lower than that of traditional firewood, due to higher fuel cost. These net benefits (private, to households) would be least negative in the stove plus fuel subsidy intervention, due to the subsidy support (-$7,827/month). Monthly private and social health benefits would be highest under the ban ($194,704 and $423,032, respectively), and the fuel subsidy option would also result in sizeable health benefits ($119,296 private and $259,593 social). Following the health benefits pattern, monthly climate ($35,160) and ecosystem savings ($12,412) would again be highest under the ban.

Turning to net benefits, then, the high private costs of a ban result in that policy intervention having the lowest private net benefits (-$268,464/month). Fuel subsidy combined with stove subsidy yields the highest and positive monthly private net benefits ($2.6 million), driven by lower private costs, especially by households that have already transitioned to LPG. However, no policy except the stove subsidy only policy (with a modest surplus of $1,266/month) delivers social net benefits overall. Also, similar to the charcoal to LPG transition in Nairobi, it is important to note here the divergent net benefits in the stove plus fuel subsidy intervention: while monthly private net benefits are the highest of all policy interventions ($2.6 million), the monthly social net benefits are lowest (-$1.2 million), driven by the high cost of providing subsidies to current LPG users (who do not require these subsidies). We again emphasize that fuel subsidies for clean fuels can be regressive by benefitting wealthier households who have already transitioned. Unlike all other policy interventions, where private net benefits excluding health are negative, under this intervention private net benefits without health are also positive due to this subsidy gain ($2.5 million/month).

At the default stove subsidy of 50%, LPG stove adoption in the stove subsidy only intervention is 45.8%. An LPG stove subsidy of 90% would increase adoption to 100%, and the relative balance of costs and benefits would remain similar, but the total amounts increase (Appendix A7). The social net benefits degrade as the subsidy increases, however. At stove subsidy levels between 50%-90%, the private net benefits would be positive for the stove and fuel subsidy intervention only while social net benefits would be negative for all policy interventions (Appendix A7). Finally, for the stove plus fuel subsidy intervention, monthly private net benefits continue to be positive as the subsidy increases, but monthly social net benefits also increasingly become negative owing to the large fuel subsidy costs imposed on the government (Figure 6, Transition 2).

As none of the policy interventions yields positive and high social net benefits, this transition is generally not favorable for Kathmandu Valley. However, firewood is likely to be the main cooking fuel for low-income households in peri-urban Kathmandu Valley. To move these households up the energy ladder, policy-makers might favor a targeted stove plus fuel subsidy intervention despite the negative social net benefits generated, as this combination delivers positive private net benefits and would thus make LPG use attractive to financially-constrained households. It is important to note that for this policy intervention, at varying levels of LPG stove subsidy, the monthly private net benefits remain positive, but the monthly social net benefits are negative throughout. Therefore, this policy should be implemented with caution in Kathmandu Valley, if at all, for the low-income populations only, which would require a sensible targeting mechanism.

Transition 3: Traditional firewood stove users to electricity: For this transition, we begin with the electric stove subsidy at 80% (Table 15). Since the stove subsidy and stove financing combined policy intervention has the maximum uptake of electric stoves (83.7%), the monthly subsidy costs are highest for that policy option ($44,755). The combination of a 50% electricity subsidy (of the unit cost) and electric stove subsidy results in fuel subsidy cost of $373,481/month to the government. A ban on traditional firewood stoves would again result in the highest monthly program costs of all policy interventions ($99,461).

As in transitions 1 and 2, the ban would entail the highest stove acquisition costs ($222,046/month), followed by the stove subsidy plus stove financing policy ($54,983/month). Monthly learning and O&M costs would be highest under the ban ($26,318 and $15,036, respectively). However, under this policy option, households that would ordinarily not switch to electric stoves would face a net monthly cost ($189,773).

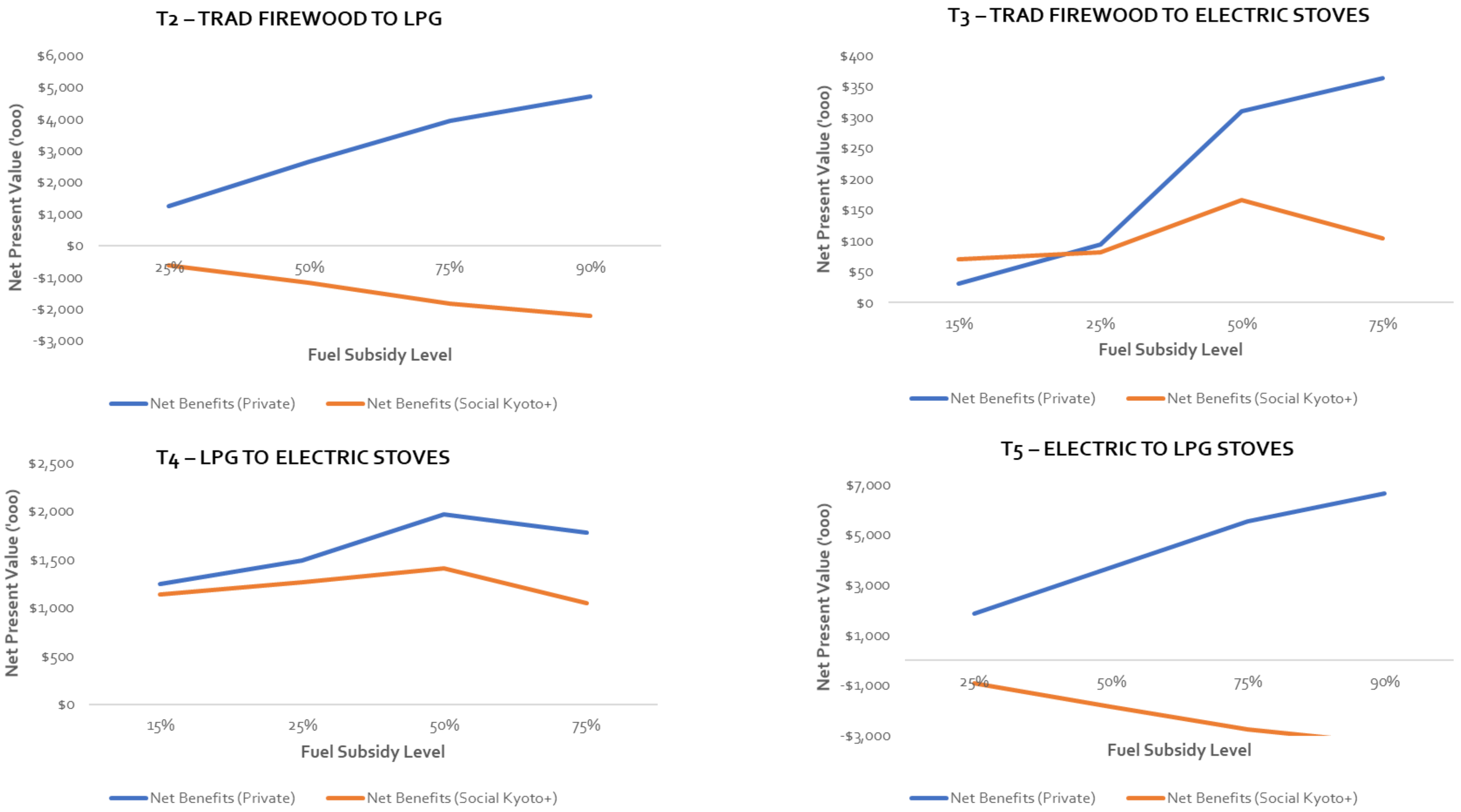


Figure 6. Net benefits at varying fuel subsidy levels for fuel subsidy plus stove subsidy policy intervention for Transitions 2-5 in Kathmandu Valley. Transition 2 (Traditional firewood stoves to LPG), Transition 3 (Traditional firewood stoves to electric stoves), Transition 4 (LPG stoves to electric stoves) and Transition 5 (Electric stoves to LPG stoves).

Table 15. Costs and benefits of Transition 3 under different policy interventions: Kathmandu Valley

	Stove subsidy	Fuel subsidy (w/ stove subsidy)	Stove financing (w/ stove subsidy)	BCC campaign (w/ stove subsidy)	Technology ban
Government subsidy costs					
Stove subsidy cost	$27,483	$41,225	$44,755	$31,801	$0
Fuel subsidy	$0	$373,481	$0	$0	$0
Program cost	$9,964	$14,946	$16,226	$18,312	$99,461
Private costs					
Capital (stove) cost	$22,813	$34,220	$54,983	$26,398	$222,046
Learning cost	$13,520	$20,280	$22,017	$15,644	$26,318
O&M cost	$7,724	$11,586	$12,578	$8,938	$15,036
Other net costs (ban-induced or for non-transitioning households)	$0	($2,913)	$0	$0	$189,773
Social costs					
Capital (stove) cost	$32,980	$49,470	$58,003	$38,161	$53,500
Program cost	$9,964	$388,427	$16,226	$18,312	$99,461
Learning cost	$3,258	$4,886	$5,305	$3,769	$6,341
O&M cost	$7,724	$11,586	$12,578	$8,938	$15,036
Other net costs (ban-induced or for non-transitioning households)	$0	($2,913)	$0	$0	$189,773
Private benefits					
Time savings	$27,594	$82,783	$44,936	$31,930	$111,908
Net fuel savings	($30,727)	$153,893	($50,038)	($35,555)	($124,614)
Private health benefits	$26,989	$135,430	$43,951	$31,229	$197,415
Social benefits					
Time savings	$27,594	$82,783	$44,936	$31,930	$111,908
Net fuel savings	($30,727)	$153,893	($50,038)	($35,555)	($124,614)
Social health benefits	$59,392	$294,649	$96,718	$68,724	$428,850
Carbon savings (Full)	$25,521	$76,562	$41,559	$29,530	$103,499
Bio savings	$3,061	$9,182	$4,984	$3,541	$12,412
Net Benefits (private)	**($20,201)**	**$308,932**	**($50,729)**	**($23,375)**	**($268,464)**
Net Benefits (social) Kyoto	**$17,177**	**$124,397**	**$23,675**	**$13,094**	**$112,230**
Net Benefits (social) Kyoto plus	**$30,915**	**$165,612**	**$46,048**	**$28,990**	**$167,946**
Net Benefits (private w/o health)	**($47,190)**	**$173,502**	**($94,679)**	**($54,604)**	**($465,879)**

On the benefits side, the ban would generate the most time savings ($111,908/month), followed by the stove plus fuel subsidy intervention ($82,783). Monthly net fuel savings would be positive only under the fuel subsidy option ($153,893), while the ban would generate the highest health benefits (private and social): 197,415/month and $428,850/month, respectively. Net carbon savings and ecosystem benefits would also be highest under the ban ($103,499 and $12,412 per month), followed by the combined stove and fuel subsidy ($76,562 and $9,182 per month).

As the ban generates the highest monthly net benefits for all categories of benefits (time, fuel, health, climate and ecosystem), unsurprisingly, its monthly social net benefits (accounting for all six pollutants) are the highest among the policy interventions ($167,946). However, owing to the high private cost to households that would not have switched to electric stoves absent a firewood ban, the technology ban option generates very negative monthly private net benefits. The fuel subsidy option yields an opposing pattern: highest and positive private net benefits ($308,932/month) as well as high social net benefits ($165,612/month). One particular challenge with the fuel subsidy intervention in this case, however, would be targeting it to cooking. Electricity is used as an input to many activities, and it would likely be impractical to attempt to target its use for cooking specifically, such that the subsidy costs would increase dramatically, relative to what is assumed here.

At the default stove subsidy of 80%, electric stove adoption in the stove subsidy only intervention is about 51.4%. Increasing the electric stove subsidy to 95% would achieve complete adoption, and the relative proportions of costs and benefits for all stove subsidy-related policy interventions would remain similar as with the default subsidy level (Appendix A8). Of the policy choices involving a stove subsidy, the stove subsidy plus fuel subsidy option yields the highest monthly social net benefits ($165,612). At all levels of electric stove subsidy between 80%-95%, the private net benefits are highest for the stove plus fuel subsidy intervention, while social net benefits are highest for a firewood ban, followed by the stove subsidy plus fuel subsidy intervention (Appendix A8).

For the stove plus fuel subsidy intervention, the monthly private net benefits become increasingly positive as the fuel subsidy increases especially at subsidy levels between 25%-50% (Figure 6, Transition 3). While the monthly social net benefits are positive at all levels of electricity subsidy, they are much lower than the monthly private net benefits, especially above 50% electricity subsidy. Owing to the practical difficulty of implementing and strictly enforcing a city-wide firewood ban, we consider the stove plus fuel subsidy intervention as the most cost-beneficial policy option, because social net benefits are high. In Figure 5 (Transition 3), we see that the monthly social and private net benefits remain positive across subsidy levels for this intervention.

Transition 4: LPG to electricity: Similar to transition 3, in this transition too we find that the combined stove subsidy and financing intervention has the highest monthly stove subsidy costs ($122,243). A 50% electricity subsidy with 50% electric stove subsidy results in a monthly government fuel subsidy cost of $0.7 million (Table 16). The combined stove subsidy and stove financing policy has the highest monthly program costs ($70,911).

Among the policy interventions involving a stove subsidy, households transitioning to electric stoves would incur the highest monthly capital cost under the financing option ($86,474). Also, monthly fuel usage for electric stoves is lower than that for LPG stoves, such that net monthly fuel savings are between $512,682 and $2 million. All the policy interventions generate positive health benefits (private or social), with the highest being under the stove plus fuel subsidy option ($4,969 private benefits and $10,664 social benefits). Similarly, the net carbon savings are highest under the stove subsidy and fuel subsidy option ($187,971 monthly carbon savings).

Table 16. Costs and benefits of Transition 4 under different policy interventions: Kathmandu Valley

	Stove subsidy	Fuel subsidy (w/ stove subsidy)	Stove financing (w/ stove subsidy)	BCC campaign (w/ stove subsidy)
Government subsidy costs				
Stove subsidy cost	$42,585	$63,877	$122,243	$62,499
Fuel subsidy	$0	$676,484	$0	$0
Program cost	$24,702	$37,054	$70,911	$57,581

Private costs				
Capital (stove) cost	$20,354	$30,531	$86,474	$29,873
Learning cost	$0	$0	$0	$0
O&M cost	$0	$0	$0	$0
Other net costs (ban-induced or for non-transitioning households)	$0	($2,143)	$0	$0
Social costs				
Capital (stove) cost	$47,489	$71,233	$143,078	$69,697
Program cost	$24,702	$713,538	$70,911	$57,581
Learning cost	$0	$0	$0	$0
O&M cost	$0	$0	$0	$0
Other net costs (ban-induced or for non-transitioning households)	$0	($2,143)	$0	$0
Private benefits				
Time savings	$0	$0	$0	$0.0
Net fuel savings	$512,682	$1,986,894	$1,471,700	$752,437
Private health benefits	$1,647	$4,969	$4,727	$2,417
Social benefits				
Time savings	$0	$0	$0	$0
Net fuel savings	$512,682	$1,986,84	$1,471,700	$752,434
Social health benefits	$3,534.5	$10,664	$10,146	$5,187
Carbon savings (Full)	$62,657	$187,971	$179,862.5	$91,958
Bio savings	$0	$0	$0	$0
Net Benefits (private)	**$493,975**	**$1,963,474**	**$1,389,953**	**$724,981**
Net Benefits (social) Kyoto	**$504,124**	**$1,395,225**	**$1,440,376**	**$718,550**
Net Benefits (social) Kyoto plus	**$506,683**	**$1,402,901**	**$1,447,720**	**$722,305**
Net Benefits (private w/o health)	**$492,328**	**$1,958,506**	**$1,385,226**	**$722,564**

On increasing the electric stove subsidy from 50%-90% (when stove adoption is 100%), the private net benefits and social net benefits also increase, and at 70% stove subsidy and above, the difference between the two categories of benefits steadily increases (Appendix A9). For the stove plus fuel subsidy intervention, on increasing the electricity subsidy levels (between 15%-75%), the positive private net benefits sharply increase beyond a 25% electricity subsidy, but social net benefits decrease especially beyond a 50% electricity subsidy (Figure 6, Transition 4). Similar to transition 3, an additional challenge with the fuel subsidy intervention in this case would be targeting it to cooking, which would very likely not be practical. Since the combined stove subsidy with financing has the highest monthly social net benefits ($1.45 million), and considerable private net benefits ($1.39 million), we consider the stove financing as the most cost-beneficial policy intervention to support this transition. Figure 5 (Transition 4) shows the monthly net benefits (private and social) for this policy intervention at varying stove subsidy levels.

Transition 5: Electric cooking users to LPG. Owing to few households switching to LPG from electricity (615 households only), the relative costs and benefits in this transition are low (Table 17). At a default LPG stove subsidy of 50%, there would be 45.8% LPG stove adoption, and monthly government stove subsidy cost would be below $100 across all policy interventions. Unlike the previous transition, the stove subsidy and BCC campaign policy intervention would have the highest monthly program costs ($147/month). The private stove cost to households switching to LPG would be negative, due to its lower cost relative to electric stoves. Similar to transition 4, there would be no time savings in this shift. Monthly net fuel savings in this transition would be negative due to the higher relative cost of LPG. Likewise, monthly private and social health benefits would be negative owing to the slightly higher emissions of LPG stoves; and finally, there would be negative climate benefits from this transition. In terms of overall benefits, the stove plus fuel subsidy policy intervention has the highest (and only positive) monthly private net benefits ($3.7 million), and all policy interventions would yield negative social net benefits.

On increasing stove subsidy levels, the relative proportions of costs and benefits for all policy interventions remain similar (Appendix A10). For the stove plus fuel subsidy intervention, the private net benefits increase with the fuel subsidy (between 25%-90%), while the social net benefits become more negative (Figure 6, Transition 5). Since none of the policy interventions yields positive and high social net benefits, this transition is not favorable for Kathmandu Valley.

Table 17. Costs and benefits of Transition 5 under different policy interventions: Kathmandu Valley

	Stove subsidy	Fuel subsidy (w/ stove subsidy)	Stove financing (w/ stove subsidy)	BCC campaign (w/ stove subsidy)
Government subsidy costs				
Stove subsidy cost	$58	$87	$99	$68
Fuel subsidy	$0	$5,532,392	$0	$0
Program cost	$79	$118	$134	$147
Private costs				
Capital (stove) cost	($701)	($1,052)	($1,769)	($825)
Learning cost	$0	$0	$0	$0
O&M cost	$0	$0	$0	$0
Other net costs (ban-induced or for non-transitioning households)	$0	($3,685,376)	$0	$0
Social costs				
Capital (stove) cost	($113)	($169)	($331)	($132)
Program cost	$79	$5,532,510	$134	$147
Learning cost	$0	$0	$0	$0
O&M cost	$0	$0	$0	$0
Other net costs (ban-induced or for non-transitioning households)	$0	($3,685,376)	$0	$0
Private benefits				
Time savings	$0	$0	$0	$0
Net fuel savings	($1,615)	($1,960)	($2,753)	($1,899)
Private health benefits	($5)	($16)	($9)	($6)
Social benefits				
Time savings	$0	$0	$0	$0
Net fuel savings	($1,615)	($1,960)	($2,753)	($1,899)
Social health benefits	($11)	($34)	($19)	($13)
Carbon savings (Full)	($197)	($592)	($336)	($232)
Bio savings	$0	$0	$0	$0
Net Benefits (private)	**($919)**	**$3,684,453**	**($993)**	**($1,081)**
Net Benefits (social) Kyoto	**($1,782)**	**($1,849,526)**	**($2,898)**	**($2,150)**
Net Benefits (social) Kyoto plus	**($1,790)**	**($1,849,550)**	**($2,911)**	**($2,159)**
Net Benefits (private w/o health)	**($914)**	**$3,684,468**	**($984)**	**($1,075)**

Discussion

Our results show that in each location the most cost-beneficial policy intervention varies by the polluting or transitional cooking technology switching away from, and the practicality of implementing a policy. Here we begin by discussing a set of criteria that could be applied to assess the relative value of different solutions aiming to accelerate the transitions previously described, before turning to a synthesis of the findings and recommendations based on our results. First, we argue that a policy intervention should achieve positive and high social net benefits. Second, for practical reasons it is important that it also generates positive private net benefits, as otherwise people will resist the transition. Moreover, sacrificing some social benefits (but not going negative, which harms society) while making the transition privately attractive is critical. Third, given the reality of tight public budgets in less-developed and even lower middle-income countries, any policy solution should not impose too much cost or burden on the government. Finally, when assessing policy options, it is imperative to consider distributional outcomes. We might favor some instances of lower or even negative social benefits if a policy is highly likely to benefit the poor rather than the rich; in addition, the poor may place especially high value on more salient, non-health benefits.

With these four objectives in mind, and also considering logistical aspects, we next examine the most cost-beneficial policy interventions in each of the studied locations, presenting a set of comparative graphs that help synthesize our results. Where policies or transitions are overlapping (e.g., charcoal to LPG or ethanol in Nairobi), we also indicate which seems more attractive and practical. We also indicate how these policy interventions perform relative to the potential in each transition, i.e., how much of the transition benefits are achieved relative to those that would occur under a complete shift from more polluting to cleaner options, as previously discussed in the results section.

Focus City in Sub-Saharan Africa: Nairobi, Kenya

In Nairobi, from the social net benefits perspective, the combined stove subsidy and financing policy option is the most cost-beneficial for transitions from traditional charcoal (to ICS charcoal) and kerosene (to LPG and ethanol), while the charcoal ban appears most cost-beneficial for the transitions from all charcoal stoves (to LPG and ethanol) (Table 18). However, implementing a charcoal ban in Kenya – where the charcoal industry is a major informal sector employer, and where the government has met with only limited success in trying to formalize it – has proven difficult in the past, and so we consider the stove subsidy with financing intervention to be the most consistently attractive from a social net benefits perspective. This policy is also generally favorable from a private net benefits perspective but the stove subsidy here is key (financing would not be sufficient to make this transition privately attractive). Fuel subsidies for ethanol and LPG (combined with stove subsidy) are also clearly attractive privately, but the downside of these policies is their high public cost relative to other interventions, as shown in Figure 7. These public costs are typically higher than the public costs for other interventions by an order of magnitude or more. This would be especially true over time as households transition and become increasingly reliant on subsidy supports, as made clear by the large burden of LPG subsidies relative to ethanol subsidies, given the large population already using LPG. In each of the five transitions, government subsidy costs in the stove subsidy plus financing option are far lower than those for the stove plus fuel subsidy option, though these public costs are somewhat higher for that intervention than for the other two policy interventions involving stove subsidy (e.g., stove subsidy alone, or subsidy plus BCC). This result stems from the financing policy reaching more customers, and thus also increasing the percentage of each transition's overall potential (Figure 8).

Of all cooking transitions in Nairobi, owing to the number of households using this dirty fuel, transitions from kerosene are potentially most favorable, and transition 3, from kerosene to LPG appears to deliver the greatest benefit, especially for the favorable stove subsidy and financing intervention. While the kerosene to ethanol transition also has high social net benefits under the favorable stove subsidy and financing option (reaching nearly $0.5 million), the ethanol market is underdeveloped at this time, and very few of Nairobi's households are currently using ethanol as their primary cooking fuel. Considerable work would be necessary to make this a viable transition, especially among the poor who would likely be most averse to trying a new, potentially "risky" fuel. Yet this transition also has potential, provided ethanol can be made accessible and available in the future.[35] Ethanol could have additional important advantages over LPG, for example, in terms of its climate change footprint (if the fuel can be sustainably produced without creating net emissions, for example arising from land clearing for production), and for energy security (in terms of reduced reliance on imported gas).

---

[35] Based on the range of price points available in the literature, we assume the average retail price of ethanol to be $1.16/liter in Nairobi (please see Table D16. for details). As of September 2020, the retail price of ethanol sold by KOKO Networks – the dominant ethanol distributor in Kenya – was somewhat lower, at $0.70/liter. Using this price point in our analysis, the fuel cost savings from a switch to ethanol would be higher, and the subsequent private and social net benefits would also be. Yet it is unclear whether the current price as set by KOKO Networks is the true cost of the fuel. Given the less-developed market for ethanol in Nairobi right now, and the fact that few households are currently using it as their primary cooking fuel, the basis for recommending an ethanol transition is low.

Table 18. Summary of cooking transitions in Nairobi and Kathmandu Valley (all outcomes reported at city scale, in U.S.$/month)

	Social net benefits (NPV)	**Private net benefits (NPV)**	**Public cost**	**Most pro-poor (NPV – private net benefits without health)**
		Panel A: Nairobi transitions		
Transition 1: Traditional charcoal to charcoal ICS	1. Technology ban ($44,034) **2. Stove financing plus subsidy ($38,596)**	**1. Stove financing plus subsidy ($14,610)** *2. BCC campaign with stove subsidy ($5,296)*	1. Stove subsidy ($1,295) *2. BCC campaign with stove subsidy ($4,822)*	**1. Stove financing plus subsidy ($11,495)** *2. BCC campaign with stove subsidy ($4,247)*
Transition 2: All charcoal to LPG	1. Technology ban ($1.1 million) **2. Stove financing plus subsidy ($421,822)**	*1. Fuel plus stove subsidy ($4.5 million)* **2. Stove financing plus subsidy ($209,758)**	1. Stove subsidy ($40,659) 2. BCC campaign with stove subsidy ($52,550)	*1. Fuel plus stove subsidy ($3.2 million)*
Transition 3: Kerosene to LPG	**1. Stove financing plus subsidy ($1.5 million)** *2. BCC campaign with stove subsidy ($1.1 million)*	*1. Fuel plus stove subsidy ($8.4 million)* **2. Stove financing plus subsidy ($1.4 million)**	1. Stove subsidy ($219,159) *2. BCC campaign with stove subsidy ($283,254)*	*1. Fuel plus stove subsidy ($6.9 million)* **2. Stove financing plus subsidy ($610,756)**
Transition 4: All charcoal to ethanol	1. Technology ban ($1 million) **2. Fuel plus stove subsidy ($589,293)**	**1. Fuel plus stove subsidy ($660,746)** 2. Stove financing plus subsidy ($72,515)	1. Stove subsidy ($19,872) 2. BCC campaign with stove subsidy ($28,506)	None
Transition 5: Kerosene to ethanol	**1. Stove financing plus subsidy ($496,497)** *2. BCC campaign with stove subsidy ($298,466)*	*1. Fuel plus stove subsidy ($1.7 million)* **2. Stove financing plus subsidy ($280,442)**	1. Stove subsidy ($107,116) *2. BCC campaign with stove subsidy ($153,654)*	*1. Fuel plus stove subsidy ($721,126)*

	Panel B: Kathmandu Valley transitions			
Transition 1: Traditional firewood to natural draft ICS	1. Stove financing plus subsidy ($74,761) **2. BCC campaign plus stove subsidy ($44,750)**	**1. BCC campaign with stove subsidy ($25,780)** *2. Stove subsidy ($21,112)*	*1. Stove subsidy ($20,105)* **2. BCC campaign with stove subsidy ($32,490)**	**1. BCC campaign with stove subsidy ($8,876)** *2. Stove subsidy ($7,269)*
Transition 2: Traditional firewood to LPG	**1. Stove subsidy ($1,266)**	*1. Fuel plus stove subsidy ($2.6 million)*	**1. Stove subsidy ($15,615)** 2. BCC campaign with stove subsidy ($24,582)	*1. Fuel plus stove subsidy ($2.5 million)*
Transition 3: Traditional firewood to electricity	1. Technology ban ($167,946) **2. Fuel plus stove subsidy ($165,612)**	**1. Fuel plus stove subsidy ($308,932)**	1. Stove subsidy ($37,447) 2. BCC campaign with stove subsidy ($50,113)	**1. Fuel plus stove subsidy ($173,502)**
Transition 4: LPG to electricity	**1. Stove financing plus subsidy ($1.45 million)** *2. Fuel plus stove subsidy ($1.4 million)*	*1. Fuel plus stove subsidy ($2 million)* **2. Stove financing plus subsidy ($1.4 million)**	1. Stove subsidy ($67,287) 2. BCC campaign with stove subsidy ($120,080)	*1. Fuel plus stove subsidy ($2 million)* **2. Stove financing plus subsidy ($1.4 million)**
Transition 5: Electricity to LPG	None	**1. Fuel plus stove subsidy ($3.7 million)**	1. Stove subsidy ($137) 2. BCC campaign with stove subsidy ($215)	**1. Fuel plus stove subsidy ($3.7 million)**

Notes: In each row, the intervention that is bolded appears most often and highest in rank (with preference given to overall social benefits in the case of ties), while italicized interventions appear equally often or second most often / highly ranked.

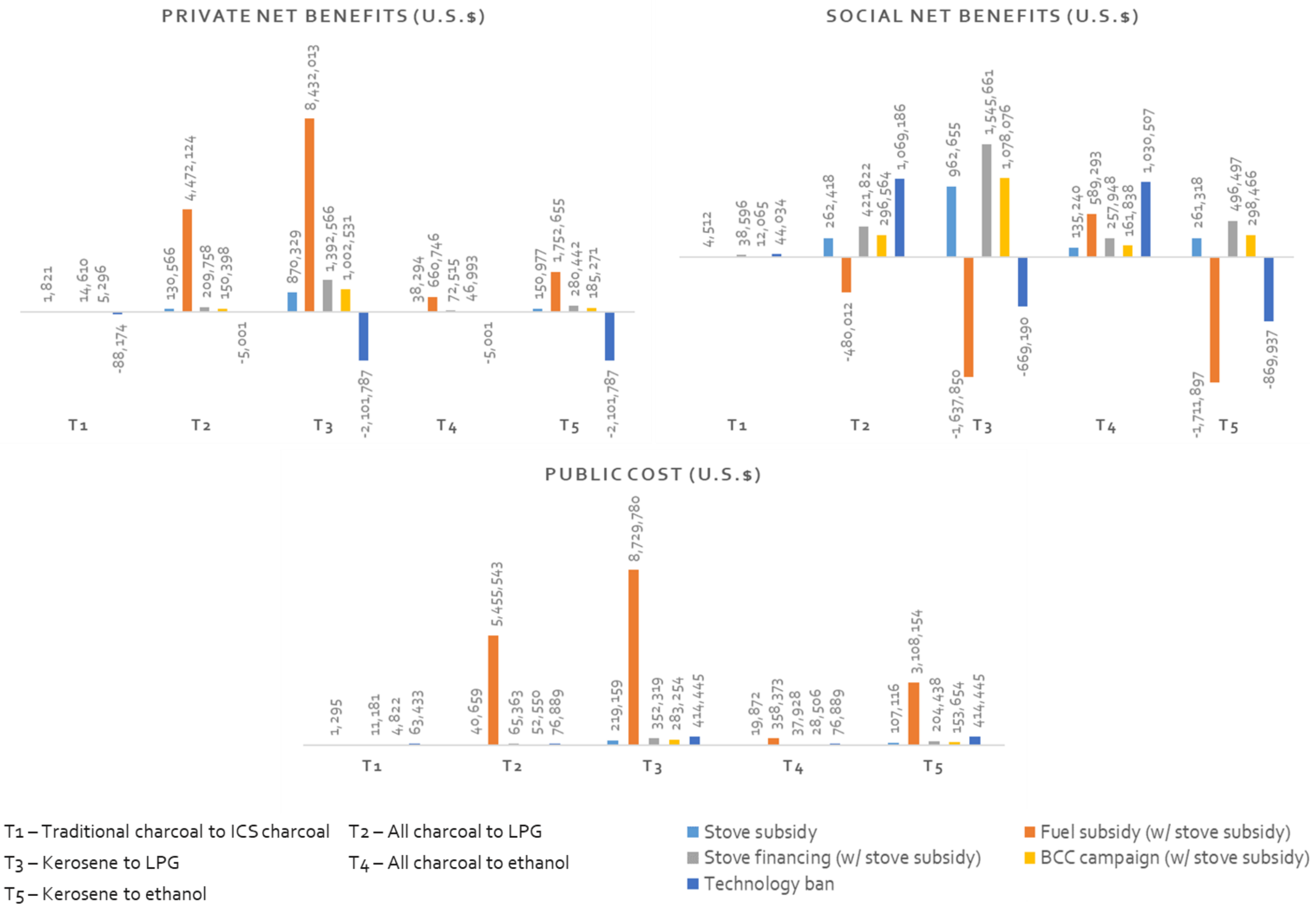


Figure 7. Comparison of relative performance of the policies for fostering different cooking transitions in Nairobi, focusing on a) Social net benefits; b) Private net benefits, and c) Net government cost (Note: For the stove and fuel subsidies, the graph shows the potential at the default levels specified in the results section).

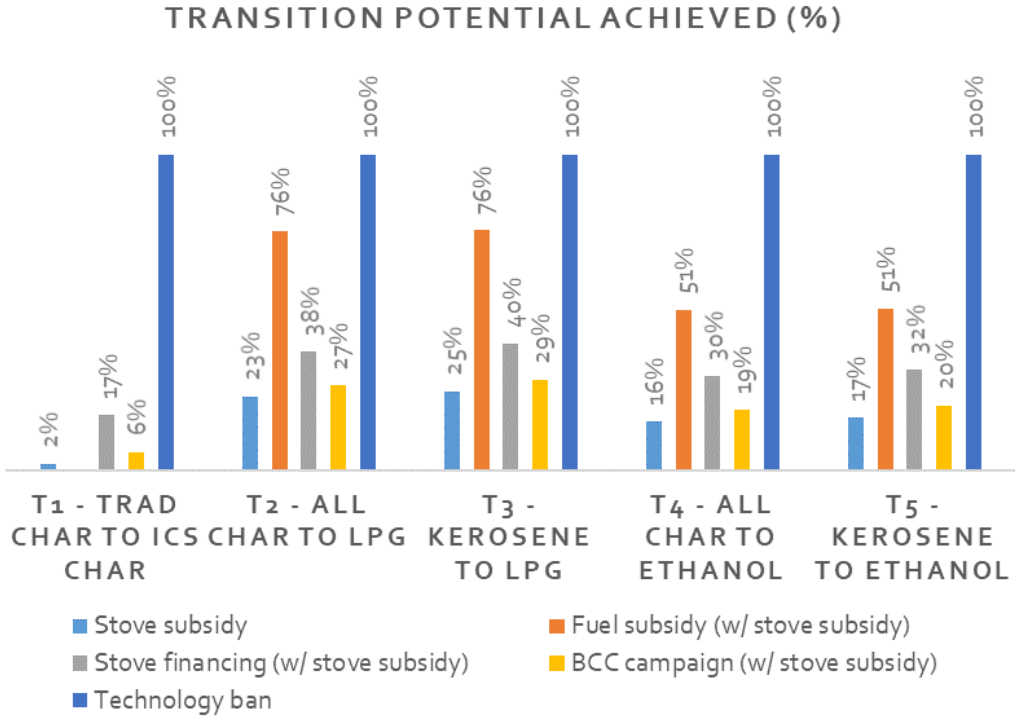


Figure 8. Potential of each transition achieved under the policy options analyzed for Nairobi, relative to a full and exclusive transition (Note: For the stove and fuel subsidies, the graph shows the potential at the default levels specified in the results section).

Transitions away from charcoal are also attractive in Nairobi, though they affect a smaller fraction of households who use it as their primary cooking fuel (mostly lower-income households in Nairobi's informal settlements). With a stove subsidy plus financing policy, the transition to LPG would have positive and high monthly social and private net benefits of $421,822 and $209,758, respectively, and the cost to the government would remain modest (especially when compared to fuel subsidy, which has negative social net benefits because of its higher subsidy costs).

Finally, though the stove and fuel subsidy policies are considered pro-poor based on a metric of private benefits that omits health benefits (Table 18), it is essential to keep in mind that subsidies for clean fuels are difficult to target well in practice, such that they end up mostly benefiting higher income households (Kar et al. 2019, Pachauri 2019). In this sense, an efficient targeting instrument that reached the poor preferentially could be especially helpful for reducing the very high public costs of clean fuel subsidies in Nairobi (Figure 7) while actually being pro-poor. India's current experience with targeting LPG subsidies to below-poverty-line households is instructive, though evidence suggests that even the subsidies used there may not be sufficiently large to foster sustained and primary use of clean fuels among the poorest of the poor (Kar et al. 2020).

Given its relatively good performance, it is also worth comparing the likely effects of a stove subsidy and finance policy to the overall potential of the transitions it would be aiming to facilitate. As shown in Figure 8, this policy option achieves only about 17% of the potential of the transition to charcoal ICS, and between 30 and 40% of the potential of the transitions from charcoal and kerosene to clean fuels. More of the potential would be achieved for a move to LPG compared to ethanol, owing to the lower adoption cost for the former. Similarly, more of the potential would be achieved in moving away from kerosene than in moving away from charcoal, owing to the relatively greater cost competitiveness of the clean fuels with kerosene (compared to charcoal). As such, some benefits would be left on the table. Compared to the potential of a full kerosene to LPG transition, which would avoid over 5,828 ALRI cases and nearly 372 COPD cases per year, the stove financing policy would avoid 2,264 ALRI cases and about 148 COPD cases, yearly. The potential ALRI mortality avoided is also higher (25 deaths) than the actual number of ALRI deaths (10 deaths) that would be avoided each year. Similarly, the yearly carbon-equivalent savings under the cost-beneficial stove financing option is about half (0.01 million tons) the potential (0.02 million tons) of this transition. It is important to note here that the potential of each transition is based on universal adoption and exclusive use of a cleaner technology, but the policy interventions account for real-world adoption, and stove or fuel stacking (e.g., partial use).

Focus City in South Asia: Kathmandu, Nepal

Turning to the case of Nepal, the transitions to electricity (from firewood – transition 3, and from LPG – transition 4) yield considerably higher social net benefits than further movements to LPG, by firewood users (Table 18). Yet the most cost-beneficial policy intervention across all five transitions is less clear than in Nairobi. For the firewood to electricity transition, the highest monthly social net benefits are realized with a ban on firewood (nearly $170,000), while for the LPG to electricity transition, these benefits are greatest with a stove subsidy plus financing policy option (yielding almost $1.5 million of net benefit). Only 11.4% of Kathmandu Valley's population relies primarily on firewood for cooking, but the high enforcement costs of a ban and the reality of stove stacking could render a firewood ban challenging. Still, the dynamics of this fuel use are notably different than those in Nairobi, where charcoal is mainly purchased (rather than collected, unlike the case of firewood in peri-urban areas around the Kathmandu Valley). For transition 3, an alternative that delivers nearly the same net social benefits as the ban, is the combined stove and fuel subsidy (with an NPV of about $165,000) (Figure 9), but this policy would also face important practical challenges since it might be difficult or even impossible to target electricity subsidies to cooking activities alone. For the remaining three transitions the monthly social net benefits are considerably lower, though financing and stove subsidies for more efficient wood-burning ICS could also be beneficial. Transitioning existing firewood users to LPG appears to have limited effects, and would likely require subsidizing LPG (Table 18). This policy however, if implemented, would need to be effectively targeted to low-income populations only, as the social net benefits at varying LPG subsidy levels are negative.

The LPG to electricity transition is particularly interesting in the case of Kathmandu, as it has a potential to generate large social and private benefits. The two preferred interventions for supporting this transition appear to be the stove subsidy and financing policy, and the combined fuel and stove subsidy. The latter, however, would likely face substantial implementation hurdles, for the reason discussed previously: targeting electricity subsidies at cooking would appear impractical without new technology. Similar to the case of fuel subsidies in Nairobi (in that case for LPG or ethanol), electricity subsidies would also be difficult to target to the poor, though countries such as Colombia do currently offer examples of use of neighborhood proxies for wealth to target such subsidies (McRae 2015).

It is interesting to note that while the transitions to electricity (from firewood – transition 3, and from LPG – transition 4) under the stove subsidy plus financing option are most favorable in the Kathmandu Valley, electricity as a primary cooking source today is quite rare. According to the last Nepal Census (2011) and our survey in peri-urban Kathmandu Valley (2019), fewer than 1% of households in the Kathmandu Valley mainly use electric cooking. Most that do are middle- to high-income households. Therefore, a distributional lens requires consideration of a policy that would spur relatively lower-income households to adopt electric cooking. BCC campaigns appear important to educate households on the benefits of cooking with electricity, from a cost and energy security perspective, and the intervention including BCC is also attractive in transition 4. The national government must also work in parallel to strengthen existing electric grid infrastructure to support cooking, and to facilitate manufacturing or import of locally-appropriate electric stoves.

Finally, comparing the actual policies to the potential of the electricity transitions in Kathmandu, we note that the firewood to electricity transition would achieve about 37% of the transition potential under the stove subsidy plus financing option, in the process saving 2.7 million hours of cooking time Figure 10). On a yearly basis, this stove financing policy would avoid 418 (out of a potential 1,587) cases of COPD. On the environmental side, this policy would save 0.03 million-tons of yearly carbon-equivalent emissions, out of a potential of 0.07 million-tons of yearly carbon-equivalent emissions. The two more preferred options from a net social benefits perspective would achieve more of the full transition potential: A firewood ban would of course achieve the full potential, and a combined fuel and stove subsidy 73%. But these policies would have the notable shortcomings as discussed above.

In contrast, for the LPG to electricity transition, the stove subsidy plus finance option would do nearly as well as the stove and fuel subsidy, at lower cost, even setting aside the challenge of targeting electricity subsidies to the poor and for cooking. The yearly carbon-equivalent savings under this cost-beneficial intervention would only reach 24% of the potential: 0.12 million tons versus the potential of 0.52 million tons.

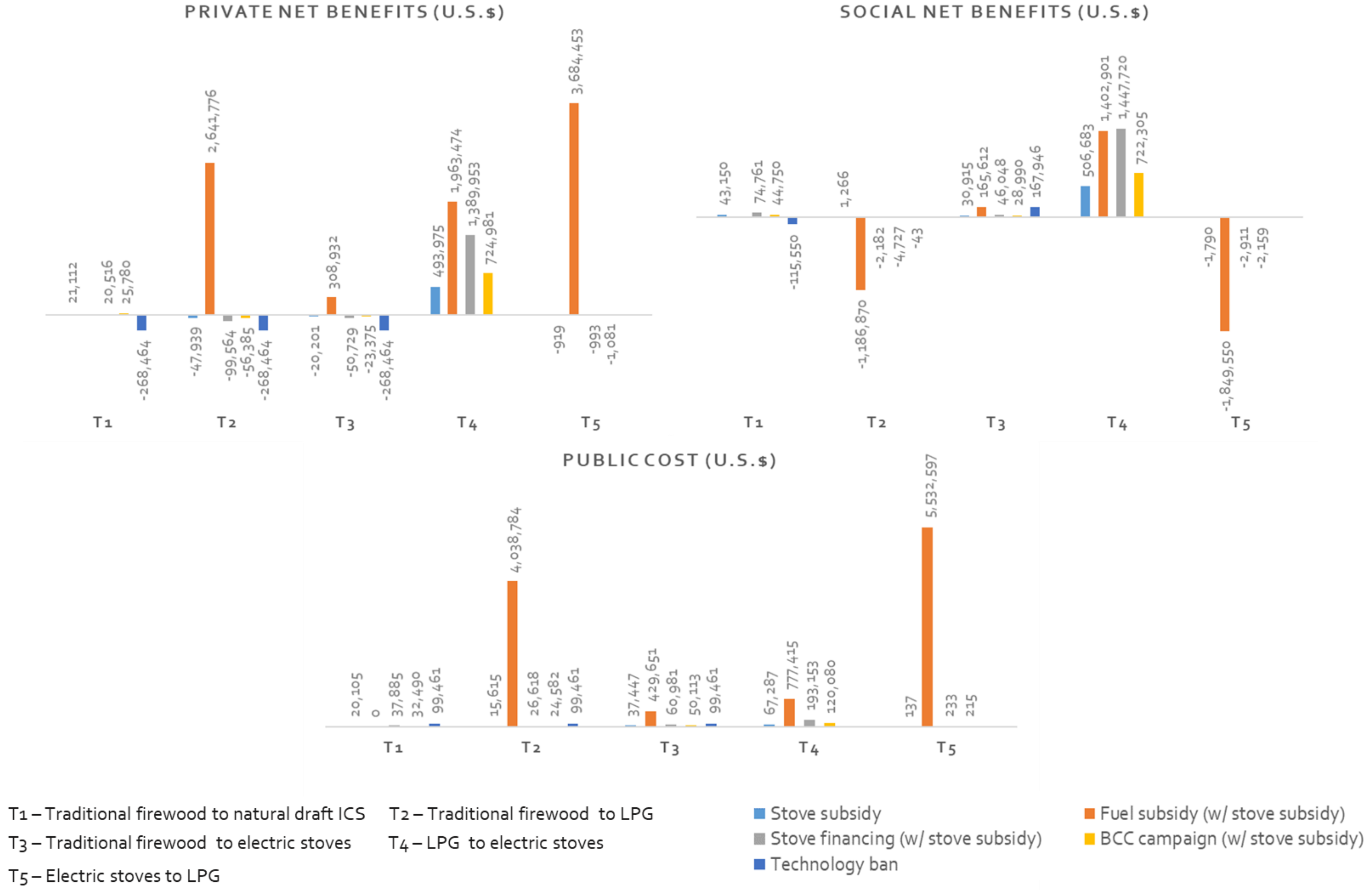


Figure 9. Comparison of relative performance of the policies for fostering different cooking transitions in Kathmandu Valley, focusing on a) Social net benefits; b) Private net benefits, and c) Net government cost (Note: For the stove and fuel subsidies, the graph shows the potential at the default levels specified in the results section).

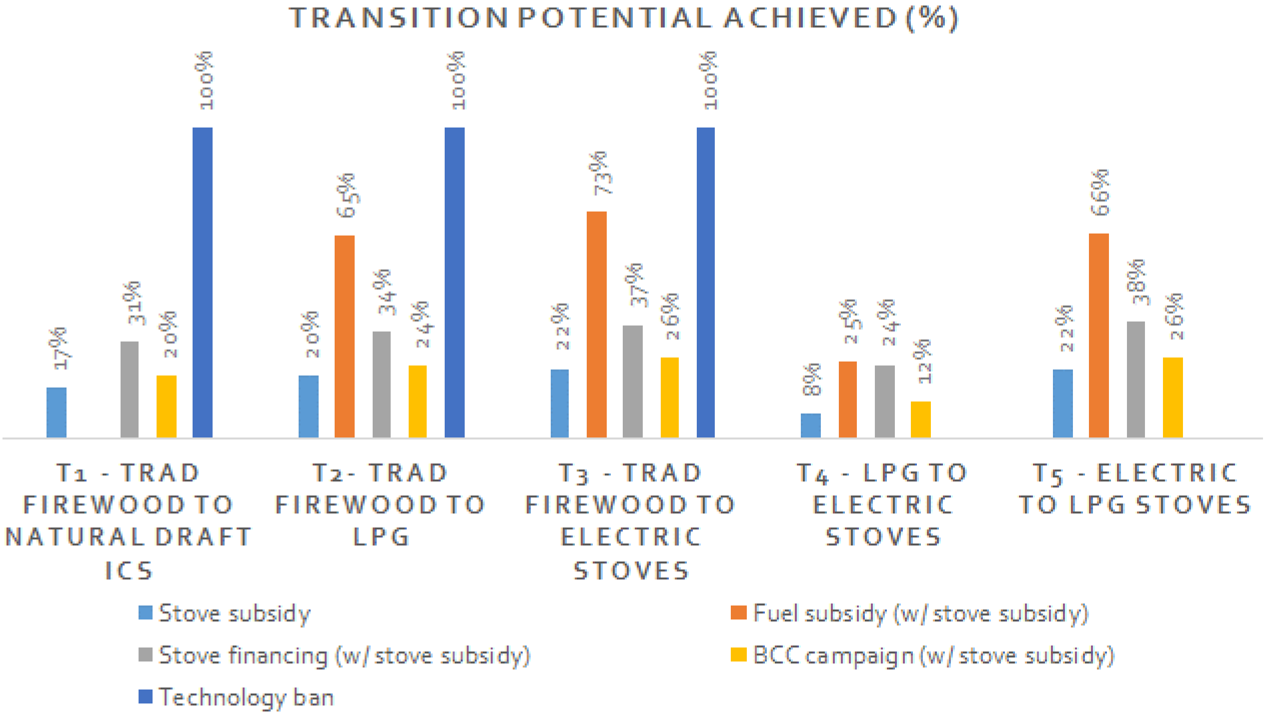


Figure 10. Potential of each transition achieved under the policy options analyzed for the Kathmandu Valley, relative to a full and exclusive transition (Note: For the stove and fuel subsidies, the graph shows the potential at the default levels specified in the results section).

Conclusion

Our analysis shows that the most socially beneficial and robust interventions, as defined by lower government cost burden, more beneficial to households in general and also to the poor, are not the same in Nairobi and the Kathmandu Valley. For Nairobi, transitions from charcoal and kerosene to LPG appear most attractive, facilitated using a combined stove subsidy and financing intervention. The former transition (from charcoal) is likely to be more beneficial among the poor, due to their greater dependence on this fuel, while the latter would help more households and therefore deliver larger benefits. Importantly, fuel subsidies for LPG are not attractive from a social net benefits perspective, and would impose a large burden on the government. These conclusions bolster the cast for the government's existing policy of a zero-rate value-added tax on LPG to reduce its cost, and the government's efforts to minimize the supply of charcoal and kerosene and increase access and awareness about LPG's benefits. While some organizations like Equity Foundation in association with LPG companies are providing loans to rural households to acquire an LPG connection, private companies are also contributing, by piloting pay-as-you-go (PAYG) technology in urban centers. There is scope for other stakeholders to finance LPG stoves through similar or other innovative options. A transition to ethanol (from the two aforementioned polluting fuels) would also be beneficial, but the higher costs of this technology and lower market development makes this transition difficult to implement for the time being.

In order to accelerate the transition to LPG, the government should study and evaluate ongoing efforts to ensure that new innovations – such as PAYG or potentially new stove subsidy and financing efforts – are effectively reaching the most relevant populations (current users of polluting fuels) rather than simply increasing options for those already using LPG. After all, these innovations address liquidity constraints and therefore increase adoption, but also come with additional costs. More work to understand and influence fuel stacking behavior is also critical, as urban households often continue to use multiple fuels for reasons that are amenable to intervention (reduced or stabilized fuel prices and ensuring fuel availability) as well as harder to shift (culture, preferences and risk management). If the government wants to make a significant push on ethanol, a careful and phased approach would be even more essential, in order to build sufficient resilience in that fuel's supply chain such that households are convinced that it can be reliably obtained when needed. Unintended consequences of ethanol promotion could be significant, in terms of increased land conversion or reduced food security, if existing farmland is used for producing biofuel.

For Kathmandu Valley, in contrast, social benefits are greatest in transitions to electric cooking, especially from LPG, but also from firewood. LPG should not be discouraged relative to firewood, but there are relatively low gains from a further push to promote LPG at this time. In Kathmandu Valley, a stove subsidy and financing policy intervention is likely to be most effective for fostering a transition to induction cooking, but BCC activities also appear attractive and necessary, due to low awareness. Indeed, electric cooking remains extremely rare and limited, and knowledge of electric cooking options and their benefits – to households and Nepal more generally – is not widespread. The potential of electric cooking resonates with the Nepal government's goal of 'expanding access to electricity and clean cooking to 100 percent of the population in 5 years' (World Bank 2018), but would also require strengthening grid distribution lines and improving substations to cater to growing electricity demand.

Alongside bolstering grid infrastructure and generating surplus electricity in hydropower projects, the government is currently considering suitable electricity pricing as one of the policy instruments to stimulate electric cooking. Such a policy would likely be costly and difficult to implement; though we found positive social benefits from subsidized electricity for cooking specifically, it would be difficult to target a subsidy in this way. Easier would be to lower the cost of induction stoves by subsidizing and developing financing options for the hardware, and supporting development of the supply chain for induction cooking technology. As in Nairobi, such efforts should be evaluated to ensure that new innovations – particularly new subsidy and financing efforts – are effective and do not have unintended adverse effects. Efforts to bolster generation and transmission infrastructure also require careful and thoughtful planning and implementation; the considerable hydropower in Nepal, for instance, would require investment in dams and infrastructure that will not always be economically and ecologically attractive (Pakhtigian et al. 2019).

Finally, as these two cases illustrate, different cities will have very different cooking situations. Thus, context-specific analysis is required to identify the most relevant cooking transitions to pursue, as well as the most attractive policies to foster those transitions. Using the framework developed and presented in these two cases, policy-makers could consider solutions for their context. The analyses could also be applied to rural locations, at a regional scale, or to examine differences between capital cities, such as Kathmandu and Nairobi, and smaller cities located in the same countries.

References

Accenture Development Partnerships. 2012. East Africa Regional Market Assessment Executive Summary. Global Alliance for Clean Cookstoves. [Accessed: December 11, 2018] Available at: http://cleancookstoves.org/resources/182.html

Ajummery Bikas Foundation. 2019. National Campaign on Market-led Promotion of Electric Cooking in CREE Areas-Campaign Paper.

Ajummery Bikas Foundation. 2019. Proceedings of National Campaign on Market-led Promotion of Electric Cooking in Community Electrification Areas-Launching Ceremony.

Anenberg, S.C., Balakrishnan, K., Jetter, J., Masera, O., Mehta, S., Moss, J. and Ramanathan, V., 2013. Cleaner cooking solutions to achieve health, climate, and economic cobenefits. *Environ. Sci. Technol.* 47, 3944-3952.

Anozie, A. N., Bakare, A. R., Sonibare, J. A., & Oyebisi, T. O. 2007. Evaluation of cooking energy cost, efficiency, impact on air pollution and policy in Nigeria. *Energy*, *32*(7), 1283-1290.

Antonel, J. and Chowdhury, Z., 2014. Measuring ambient particulate matter in three cities in Cameroon, Africa. *Atmospheric Environment*, *95*, pp.344-354.

Bacon, R., Bhattacharya, S., & Kojima, M. 2010. Expenditure of low-income households on energy: Evidence from Africa and Asia. Extractive Industries for Development Series # 16, World Bank, Washington, DC. 2010.

Bailis, R., Cowan, A., Berrueta, V., & Masera, O. 2009. Arresting the killer in the kitchen: the promises and pitfalls of commercializing improved cookstoves. *World Development*, *37*(10), 1694-1705.

Bailis, R., Drigo, R., Ghilardi, A. and Masera, O., 2015. The carbon footprint of traditional woodfuels. *Nature Climate Change*, *5*(3), p.266.

Barrington-Leigh, C., Baumgartner, J., Carter, E., Robinson, B. E., Tao, S., & Zhang, Y. 2019. An evaluation of air quality, home heating and well-being under Beijing's programme to eliminate household coal use. *Nature Energy*, *4*(5), 416-423.

Bates, M. N., Pope, K., Sijali, T. R., Pokhrel, A. K., Pillarisetti, A., Lam, N. L., & Verma, S. C. 2019. Household fuel use and pulmonary tuberculosis in western Nepal: A case-control study. *Environmental research*, *168*, 193-205.

Beltramo, T., Blalock, G., Levine, D. I., & Simons, A. M. 2015. The effect of marketing messages and payment over time on willingness to pay for fuel-efficient cookstoves. *Journal of Economic Behavior & Organization*, *118*, 333-345.

Bensch, G and J Peters. 2015. The intensive margin of technology adoption–Experimental evidence on improved cooking stoves in rural Senegal. *Journal of Health Economics*, 42, 44-63.

Bensch, G and J Peters. 2020. One-off subsidies and long-run adoption—Experimental evidence on improved cooking stoves in Senegal. *American Journal of Agricultural Economics*, 102(1), 72-90.

Bhandari, R., & Pandit, S. 2018. Electricity as a Cooking Means in Nepal—A Modelling Tool Approach. *Sustainability*, *10*(8), 2841.

Boardman, A.E., Greenberg, D., Vining, A., Weimer, D., 2005. Cost-Benefit Analysis: Concepts and Practice. Prentice Hall.

Bonjour, S., Adair-Rohani, H., Wolf, J., Bruce, N.G., Mehta, S., Prüss-Ustün, A., Lahiff, M., Rehfuess, E.A., Mishra, V. and Smith, K.R., 2013. Solid fuel use for household cooking: country and regional estimates for 1980–2010. *Environmental Health Perspectives*, 121(7), p.784.

Budya, H., & Arofat, M. Y. 2011. Providing cleaner energy access in Indonesia through the megaproject of kerosene conversion to LPG. *Energy Policy*, *39*(12), 7575-7586.

Burnett, R.T., Pope III, C.A., Ezzati, M., Olives, C., Lim, S.S., Mehta, S., Shin, H.H., Singh, G., Hubbell, B., Brauer, M. and Anderson, H.R., 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environmental Health Perspectives*, *122*(4), p.397.

Business Daily. 2020. IMF pushes for higher prices of maize flour, cooking gas. [Accessed: March 18, 2020] Available at: https://www.businessdailyafrica.com/economy/IMF-pushes-for-higher-prices-maize-flour-gas/3946234-5421024-m817smz/index.html

Cameron, C., Pachauri, S., Rao, N. D., McCollum, D., Rogelj, J., & Riahi, K. 2016. Policy trade-offs between climate mitigation and clean cook-stove access in South Asia. *Nature Energy*, *1*(1), 1-5.

Chafe, Z.A., Brauer, M., Klimont, Z., Van Dingenen, R., Mehta, S., Rao, S., Riahi, K., Dentener, F. and Smith, K.R., 2014. Household cooking with solid fuels contributes to ambient PM2. 5 air pollution and the burden of disease. *Environmental Health Perspectives*, *122*(12), p.1314.

Clean Cooking Alliance. 2018. Country Profiles-Kenya. [Accessed: December 11, 2018] Available at: http://cleancookstoves.org/country-profiles/focus-countries/4-kenya.html

Clean Cooking Alliance. 2019. Clean Cooking Forum 2019 Newsletter. [Accessed: April 6, 2020]. Available at: https://www.cleancookingalliance.org/about/news/11-25-2019-clean-cooking-forum-2019-newsletter.html

Clean Cooking Alliance. 2020. Assessment on the readiness for widespread adoption of electric cooking in Nepal – Request for Proposals (RFP).

Clean Cooking Association of Kenya and Kenya Ministry of Energy. 2019. Kenya Cooking Sector Study: Assessment of the Supply and Demand of Cooking Solutions at the Household Level. [Accessed: November 14, 2019]. Available at: https://www.eedadvisory.com/wp-content/uploads/2019/11/moe-2019-cooking-sector-study-.pdf

DFRS. 2014a. Churia forests of Nepal. In Forest resource assessment (FRA), Department of Forest research and survey (DFRS), Ministry of Forest and Soil Conservation (MoFSC), Government of Nepal, Kathmandu.

DFRS. 2014b. Terai forests of Nepal. In Forest resource assessment (FRA), Department of Forest Research and Survey (DFRS), MoFSC., Government of Nepal, Kathmandu.

Disrupt Africa. 2020. Kenya's KOKO Networks rolls out clean fuel provision service across Nairobi. [Accessed: September 30, 2020] Available at: https://disrupt-africa.com/2020/09/kenyas-koko-networks-rolls-out-clean-fuel-provision-service-across-nairobi/?emci=21eaa128-8002-eb11-96f5-00155d03affc&emdi=79655590-3603-eb11-96f5-00155d03affc&ceid=3847330

EnDev. 2012. Dynamic market for improved cooking devices in Kenya.

Energizing Development. 2012. Dynamic market for improved cooking devices in Kenya. [Accessed: December 11, 2018] Available at: http://cleancookstoves.org/resources/191.html

Energy and Petroleum Regulatory Authority. 2019. The Petroleum (Liquefied Petroleum Gas) Regulations 2019. [Accessed: April 7, 2020]. Available at: https://www.epra.go.ke/download/the-petroleum-act-the-petroleum-liquefied-petroleum-gas-regulations-2019/

Ernst and Young. 2020. Kenya enacts Finance Act, 2020. [Accessed: September 25, 2020] Available at: https://www.ey.com/en_gl/tax-alerts/kenya-enacts-finance-act-2020

Evans, W. D., Young, B. N., Johnson, M. A., Jagoe, K. A., Charron, D., Rossanese, M., ... & Ipe, J. (2020). The Shamba Chef Educational Entertainment Program to Promote Modern Cookstoves in Kenya: Outcomes and Dose–Response Analysis. *International Journal of Environmental Research and Public Health*, *17*(1), 162.

Ferraro, P.J., Lawlor, K., Mullan, K.L. and Pattanayak, S.K., 2011. Forest figures: Ecosystem services valuation and policy evaluation in developing countries. *Review of Environmental Economics and Policy*, *6*(1), pp.20-44.

Gaita, S. M., Boman, J., Gatari, M. J., Pettersson, J. B., & Janhäll, S. 2014. Source apportionment and seasonal variation of PM 2.5 in a Sub-Saharan African city: Nairobi, Kenya. *Atmospheric Chemistry and Physics*, *14*(18), 9977-9991.

Global Alliance for Clean Cookstoves. 2018. Country Profiles, Country-Level Data. [Accessed: October 22, 2018]. Available: http://cleancookstoves.org/country-profiles/59-nepal.html

Goodwin, N. J., O'Farrell, S. E., Jagoe, K., Rouse, J., Roma, E., Biran, A., & Finkelstein, E. A. 2015. Use of behavior change techniques in clean cooking interventions: a review of the evidence and scorecard of effectiveness. *Journal of health communication*, *20*(sup1), 43-54.

Gould, C. F., Schlesinger, S., Toasa, A. O., Thurber, M., Waters, W. F., Graham, J. P., & Jack, D. W. 2018. Government policy, clean fuel access, and persistent fuel stacking in Ecuador. *Energy for Sustainable Development*, *46*, 111-122.

Government of Kenya. 2009. Forest (Charcoal) Rules, 2009 [L.N. 186/2009.].

Government of Kenya. 2018. National Climate Change Action Plan (Kenya): 2018-2022. Nairobi: Ministry of Environment and Forestry.

Government of Kenya. 2018. A Report on Forest Resources Management and Logging Activities in Kenya: Findings and Recommendations. Nairobi: Ministry of Environment and Forestry.

Government of Kenya. 2019. Kenya Gazette Supplement: Acts, 2019. The Energy Act 2019. [Accessed: March 18, 2020] Available at: https://kplc.co.ke/img/full/o8wccHsFPaZ3_ENERGY%20ACT%202019.pdf

Government of Nepal. 2012. National Population and Housing Census 2011 (National Report). National Planning Commission Secretariat, Central Bureau of Statistics.

Government of Nepal. 2014. Central Bureau of Statistics. Population Monograph of Nepal-Volume I. [Accessed: October 22, 2018]. Available: http://cbs.gov.np/image/data/Population/Population%20Monograph%20of%20Nepal%202014/Population%20Monograph%20of%20Nepal%202014%20Volume%20I%20FinalPrintReady1.pdf

Government of Nepal. 2016. Renewable Energy Subsidy Policy, 2073 BS. Ministry of Population and Environment. [Accessed: July 5, 2019]. Available: https://www.aepc.gov.np/uploads/docs/2018-06-19_RE%20Subsidy%20Policy,%202073%20(English).pdf

Government of Nepal. 2017. Ministry of Population and Environment. Biomass Energy Strategy 2017.

Government of Nepal. 2018. Ministry of Energy, Water Resources and Irrigation. Current Status and the Roadmap for the Future. White Paper. Kathmandu.

Government of Nepal. 2019. Alternative Energy Promotion Center. [Accessed: July 5, 2019]. Available: https://www.aepc.gov.np/improved-cooking-stoves

Government of Nepal. 2019. 15th Plan Approach Paper [Accessed: July 6, 2019]. Available: https://www.npc.gov.np/images/category/15th_Plan_Approach_Paper2.pdf

Government of Nepal. 2020. Ministry of Forests and Environment, Department of Environment, Air Quality Monitoring. [Accessed: September 25, 2020]. Available: http://pollution.gov.np/#/home?_k=p4h6jd

Gupta, G., & Köhlin, G. 2006. Preferences for domestic fuel: analysis with socio-economic factors and rankings in Kolkata, India. *Ecological Economics*, *57*(1), 107-121.

Hughes-Cromwick, E. L. 1985. Nairobi households and their energy use: an economic analysis of consumption patterns. *Energy Economics*, *7*(4), 265-278.

Hutton, G., Rehfuess, E. and Tediosi, F., 2007. Evaluation of the costs and benefits of interventions to reduce indoor air pollution. *Energy for Sustainable Development*, 11(4), pp.34-43.

Institute for Health Metrics and Evaluation. 2017. Global Burden of Disease Profile: Kenya. [Accessed: December 31, 2019]. Available at:
http://www.healthdata.org/kenya

Kar, A., Pachauri, S., Bailis, R. and Zerriffi, H., 2020. Capital cost subsidies through India's Ujjwala cooking gas programme promote rapid adoption of liquefied petroleum gas but not regular use. *Nature Energy*, *5*(2), pp.125-126.

Karekezi, S., Kimani, J., & Onguru, O. 2008. Energy access among the urban poor in Kenya. *Energy for Sustainable Development*, *12*(4), 38-48.

IEA, IRENA, UNSD, World Bank, WHO. 2020. Tracking SDG 7: The Energy Progress Report. World Bank, Washington DC.

Institute for Health Metrics and Evaluation (IHME). GBD Compare Data Visualization. Seattle, WA: IHME, University of Washington, 2016. Available from http:// vizhub.healthdata.org/gbd-compare. Accessed on November 2, 2020.

Interagency Working Group on Social Cost of Carbon, 2015. Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. United States Government, Washington, USA.

Islam, Md. R., Jayarathne, T., Simpson, I. J., Werden, B., Maben, J., Gilbert, A., Praveen, P. S., Adhikari, S., Panday, A. K., Rupakheti, M., Blake, D. R., Yokelson, R. J., DeCarlo, P. F., Keene, W. C., and Stone, E. A.: 2019. Ambient air quality in the Kathmandu Valley, Nepal during the pre-monsoon: Concentrations and sources of particulate matter and trace gases, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-333, in review.

Jeuland, M.A. and Pattanayak, S.K., 2012. Benefits and costs of improved cookstoves: assessing the implications of variability in health, forest and climate impacts. *PloS one*, *7*(2).

Jeuland, M. A., Bhojvaid, V., Kar, A., Lewis, J. J., Patange, O., Pattanayak, S. K., ... & Ramanathan, V. 2015. Preferences for improved cook stoves: Evidence from rural villages in north India. *Energy Economics*, 52, 287-298.

Jeuland, M., Soo, J.S.T. and Shindell, D., 2018. The need for policies to reduce the costs of cleaner cooking in low income settings: Implications from systematic analysis of costs and benefits. *Energy Policy*, *121*, pp.275-285.

Jeuland, M., Pattanayak, S.K. and Peters, J., 2020. Do improved cooking stoves inevitably go up in smoke? Evidence from India and Senegal. *VoxDev*, *Published on April 6, 2020*. [Accessed: May 18, 2020]. Available: https://voxdev.org/topic/energy-environment/do-improved-cooking-stoves-inevitably-go-smoke-evidence-india-and-senegal

Jeuland, M., Fetter, T.R., Li, Y., Pattanayak, S.K., Usmani, F. and SETI Study Group. 2020. Is energy the golden thread? A systematic review of the impacts of modern and traditional energy use in low- and middle-income countries. *In Review*.

Kar, A., Pachauri, S., Bailis, R. and Zerriffi, H., 2019. Using sales data to assess cooking gas adoption and the impact of India's Ujjwala programme in rural Karnataka. *Nature Energy*, *4*(9), pp.806-814.

Kar, A., Pachauri, S., Bailis, R. and Zerriffi, H., 2020. Capital cost subsidies through India's Ujjwala cooking gas programme promote rapid adoption of liquefied petroleum gas but not regular use. *Nature Energy*, *5*(2), pp.125-126.

Karanja, A., & Gasparatos, A. 2019. Adoption and impacts of clean bioenergy cookstoves in Kenya. *Renewable and Sustainable Energy Reviews*, *102*, 285-306.

Kathmandu Post.2019. Electricity Regulatory Commission begins work to formulate directives [Accessed: November 13, 2019]. Available: https://kathmandupost.com/money/2019/06/12/electricity-regulatory-commission-begins-work-to-formulate-directives

Katoto, P.D., Byamungu, L., Brand, A.S., Mokaya, J., Strijdom, H., Goswami, N., De Boever, P., Nawrot, T.S. and Nemery, B., 2019. Ambient air pollution and health in Sub-Saharan Africa: Current evidence, perspectives and a call to action. *Environmental research*.

Kebede, B., Bekele, A., & Kedir, E. 2002. Can the urban poor afford modern energy? The case of Ethiopia. *Energy policy*, *30*(11-12), 1029-1045.

Kenya Air Quality Management Sub-Committee Report. 2017. National Committee on Air Quality Management and Coordination workshop. 20th-23rd February, 2017, Naivasha, Kenya.

Kenya Integrated Household Budget Survey. 2015. Kenya National Bureau of Statistics-Ministry of Devolution and National Planning. [Accessed: August 2, 2018]. Available at: http://statistics.knbs.or.ke/nada/index.php/catalog/88/data_dictionary

Kenya National Bureau of Statistics. 2018. Basic Report: Based on 2015/16 Kenya Integrated Household Budget Survey. March 2018.

Kenya Revenue Authority. 2020. Presumptive Tax and Turnover Tax. [Accessed: April 7, 2020]. Available at: https://www.kra.go.ke/en/individual/filing-paying/types-of-taxes/presumptive-tax

KOKO Networks. 2018. Centralized bottling: Not an answer for ethanol cooking fuel. [Accessed: September 30, 2020]. Available at: https://kokonetworks.com/news/centralised-bottling-not-the-answer-for-ethanol-cooking-fuel/

Larsen, B., 2014. Air Pollution Assessment Paper: Benefits and costs of the air pollution targets for the post 2015 development agenda: Post 2015 Consensus. *Copenhagen Consensus Center: Copenhagen, Denmark.*

Levine, D. I., Beltramo, T., Blalock, G., Cotterman, C., & Simons, A. M. 2018. What impedes efficient adoption of products? Evidence from randomized sales offers for fuel-efficient cookstoves in Uganda. *Journal of the European Economic Association*, *16*(6), 1850-1880.

Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., Shibuya, K., Adair-Rohani, H., AlMazroa, M.A., Amann, M., Anderson, H.R., Andrews, K.G. and Aryee, M., 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *The Lancet*, 380(9859), pp.2224-2260.

Mahapatra, P. S., Puppala, S. P., Adhikary, B., Shrestha, K. L., Dawadi, D. P., Paudel, S. P., & Panday, A. K. 2019. Air quality trends of the Kathmandu Valley: A satellite, observation and modeling perspective. *Atmospheric environment*, *201*, 334-347.

Malla, M. B., Bruce, N., Bates, E., & Rehfuess, E. 2011. Applying global cost-benefit analysis methods to indoor air pollution mitigation interventions in Nepal, Kenya and Sudan: Insights and challenges. *Energy Policy*, *39*(12), 7518-7529.

Martin, W.J., Hollingsworth, J.W. and Ramanathan, V., 2014. Household air pollution from cookstoves: impacts on health and climate. In *Global Climate Change and Public Health* (pp. 237-255). Humana Press, New York, NY.

McRae, S. 2015. Infrastructure Quality and the Subsidy Trap. *American Economic Review*, 105(1), January 2015, 35–66.

Mkoma, S.L., Kawamura, K. and Fu, P.Q., 2013. Contributions of biomass/biofuel burning to organic aerosols and particulate matter in Tanzania, East Africa, based on analyses of ionic species, organic and elemental carbon, levoglucosan and mannosan. *Atmospheric chemistry and physics*, *13*(20), pp.10325-10338.

Ministry of Health, Nepal; New ERA; and ICF. 2017. *Nepal Demographic and Health Survey 2016*. Kathmandu, Nepal: Ministry of Health, Nepal.

Mortimer, K., Ndamala, C. B., Naunje, A. W., Malava, J., Katundu, C., Weston, W., ... & Wang, D. 2017. A cleaner burning biomass-fuelled cookstove intervention to prevent pneumonia in children under 5 years old in rural Malawi (the Cooking and Pneumonia Study): a cluster randomised controlled trial. *The Lancet*, *389*(10065), 167-175.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V.., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, USA.

Naghavi, M., Abajobir, A. A., Abbafati, C., Abbas, K. M., Abd-Allah, F., Abera, S. F., ... & Ahmadi, A. 2017. Global, regional, and national age-sex specific mortality for 264 causes of death, 1980–2016: a systematic analysis for the Global Burden of Disease Study 2016. *The Lancet*, 390(10100), 1151-1210.

Naidja, L., Ali-Khodja, H. and Khardi, S., 2018. Sources and levels of particulate matter in North African and Sub-Saharan cities: a literature review. *Environmental Science and Pollution Research*, *25*(13), pp.12303-12328.

Nepal, M., Nepal, A., & Grimsrud, K. 2011. Unbelievable but improved cookstoves are not helpful in reducing firewood demand in Nepal. *Environment and Development Economics*, *16*(1), 1-23.

Nerini, F. F., Ray, C., & Boulkaid, Y. 2017. The cost of cooking a meal. The case of Nyeri County, Kenya. *Environmental Research Letters*, *12*(6), 065007.

Ngui, D., Mutua, J., Osiolo, H., & Aligula, E. 2011. Household energy demand in Kenya: An application of the linear approximate almost ideal demand system (LA-AIDS). *Energy policy*, *39*(11), 7084-7094.

Ouedraogo, B. 2006. Household energy preferences for cooking in urban Ouagadougou, Burkina Faso. *Energy policy*, *34*(18), 3787-3795.

Pachauri, S., Rao, N. D., & Cameron, C. 2018. Outlook for modern cooking energy access in Central America. *PloS one*, *13*(6), e0197974.

Pachauri, S. 2019. Varying impacts of China's coal ban. *Nature Energy*, *4*(5), 356-357.

Pakhtigian, E. L., Jeuland, M., Bharati, L., & Pandey, V. P. 2019. The role of hydropower in visions of water resources development for rivers of Western Nepal. *International Journal of Water Resources Development*, 1-28.

Pakhtigian, E.L., Jeuland, M., Dhaubanjar, S. and Pandey, V.P., 2019. Balancing intersectoral demands in basin-scale planning: The case of Nepal's western river basins. *Water Resources and Economics*, p.100152.

Pant, K. P. 2007. Valuing interventions to reduce indoor air pollution—fuelwood, deforestation, and health in Rural Nepal. *The Pakistan Development Review*, 1169-1187

Pant, K. P. 2012. Cheaper fuel and higher health costs among the poor in rural Nepal. *Ambio*, *41*(3), 271-283

Parajuly, K. 2016. Pollution: clean up the air in Kathmandu. *Nature*, *533*(7603), 321.

Pattanayak, S. K., Jeuland, M., Lewis, J. J., Usmani, F., Brooks, N., Bhojvaid, V., ... & Ramanathan, N. 2019. Experimental evidence on promotion of electric and improved biomass cookstoves. *Proceedings of the national Academy of Sciences*, *116*(27), 13282-13287.

Pokhrel, A. K., Smith, K. R., Khalakdina, A., Deuja, A., & Bates, M. N. 2005. Case–control study of indoor cooking smoke exposure and cataract in Nepal and India. *International journal of epidemiology*, *34*(3), 702-708.

Pokhrel, A. K., Bates, M. N., Verma, S. C., Joshi, H. S., Sreeramareddy, C. T., & Smith, K. R. 2009. Tuberculosis and indoor biomass and kerosene use in Nepal: a case–control study. *Environmental health perspectives*, *118*(4), 558-564.

Pope D, Johnson M, Fleeman N, Jagoe K, Ludolph R, Lewis J, Adair-Rohani A. 2020. Impact of household stove and fuel technologies on particulate and carbon monoxide concentration and exposures, a systematic review and analysis. In preparation.

Saud, B., & Paudel, G. 2018. The Threat of Ambient Air Pollution in Kathmandu, Nepal. *Journal of Environmental and Public Health*, 2018.

Shrestha, I. L., & Shrestha, S. L. 2005. Indoor air pollution from biomass fuels and respiratory health of the exposed population in Nepalese households. *International journal of occupational and environmental health*, *11*(2), 150-160.

Rehfuess, E.A., Puzzolo, E., Stanistreet, D., Pope, D. and Bruce, N.G., 2013. Enablers and barriers to large-scale uptake of improved solid fuel stoves: a systematic review. *Environmental Health Perspectives*, *122*(2), pp.120-130.

Rhodes, E. L., Dreibelbis, R., Klasen, E., Naithani, N., Baliddawa, J., Menya, D., ... & Kennedy, C. 2014. Behavioral attitudes and preferences in cooking practices with traditional open-fire stoves in Peru, Nepal, and Kenya: implications for improved cookstove interventions. *International journal of environmental research and public health*, 11(10), 10310-10326.

Rosenthal J, Quinn A, Grieshop AP, Pillarisetti A, Glass RI. 2018. Clean cooking and the SDGs: Integrated analytical approaches to guide energy interventions for health and environment goals. *Energy for Sustainable Development*, 1;42:152-9.

RSM International Association. 2019. Kenya Finance Act, 2019. [Accessed: April 7, 2020]. Available at: https://www.rsm.global/kenya/insights/tax-insights/kenya-finance-act-2019

Schwela, D., 2012. *Review of Urban Air Quality in Sub-Saharan Africa Region: Air Quality Profile of SSA Countries*. World Bank.

Smith, K.R., Frumkin, H., Balakrishnan, K., Butler, C.D., Chafe, Z.A., Fairlie, I., Kinney, P., Kjellstrom, T., Mauzerall, D.L., McKone, T.E. and McMichael, A.J., 2013. Energy and human health. *Annual Review of Public Health*, *34*, pp.159-188.

Sustainable Energy for All Kenya Action Agenda. 2016.

The Kenya Gazette. 2018. The Forest Conservation and Management Act (No. 34 of 2016). Published by Authority of the Republic of Kenya. Nairobi, 26th February, 2018.

The Star. 2020. Proposed taxes will negatively impact the clean cooking sector. [Accessed: September 25, 2020]. Available at: https://www.the-star.co.ke/opinion/2020-06-03-proposed-taxes-will-negatively-impact-the-clean-cooking-sector/

Treiber, M. U., Grimsby, L. K., & Aune, J. B. 2015. Reducing energy poverty through increasing choice of fuels and stoves in Kenya: Complementing the multiple fuel model. *Energy for Sustainable Development*, *27*, 54-62.

Troncoso, K., & da Silva, A. S. 2017. LPG fuel subsidies in Latin America and the use of solid fuels to cook. *Energy Policy*, *107*, 188-196.

U.S. Embassy Kathmandu. 2020. Air Quality Monitor. [Accessed: September 25, 2020]. Available: https://np.usembassy.gov/embassy/air-quality-monitor/

United States Environmental Protection Agency. 2020. Particulate Matter ($PM_{2.5}$) Trends. [Accessed: November 3, 2020]. Available: https://www.epa.gov/air-trends/particulate-matter-pm25-trends

Usmani, F., Steele, J., & Jeuland, M. 2017. Can economic incentives enhance adoption and use of a household energy technology? Evidence from a pilot study in Cambodia. *Environmental Research Letters*, *12*(3), 035009.

Van der Kroon, B., Brouwer, R., & Van Beukering, P. J. 2014. The impact of the household decision environment on fuel choice behavior. *Energy Economics*, 44, 236-247.

Van Vliet, E.D.S. and Kinney, P.L., 2007. Impacts of roadway emissions on urban particulate matter concentrations in sub-Saharan Africa: new evidence from Nairobi, Kenya. *Environmental Research Letters*, *2*(4), p.045028.

Viscusi, W.K. and Aldy, J.E., 2003. The value of a statistical life: a critical review of market estimates throughout the world. *Journal of Risk and Uncertainty*, *27*(1), pp.5-76.

Weyant, C.L., Thompson, R., Lam, N.L., Upadhyay, B., Shrestha, P., Maharjan, S., Rai, K., Adhikari, C., Fox, M.C. and Pokhrel, A.K., 2019. In-Field Emission Measurements from Biogas and Liquified Petroleum Gas (LPG) Stoves. *Atmosphere*, *10*(12), p.729.

World Bank. 2015. Nepal: Scaling Up Electricity Access through Mini and Micro Hydropower Applications: A strategic stock-taking and developing a future roadmap. [Accessed: July 7, 2019]. Available at: http://documents.worldbank.org/curated/en/650931468288599171/pdf/96844-REVISED-v1-Micro-Hydro-Report-0625-2015-Final.pdf

World Bank. 2018. DataBank-online tool for visualization and analysis. [Accessed: January 17, 2019]. Available at: https://data.worldbank.org/indicator/EN.ATM.CO2E.SF.KT?locations=KE&view=map

World Bank. 2018. Kenya launches ambitious plan to provide electricity to all citizens by 2022. [Accessed: April 6, 2020]. Available at: https://www.worldbank.org/en/news/press-release/2018/12/06/kenya-launches-ambitious-plan-to-provide-electricity-to-all-citizens-by-2022

World Bank. 2018. International Development Association Program Document for a Proposed Development Policy Credit in the Amount of SDR 71.2 Million (U.S.$ 100 Million Equivalent) to Nepal for a First Programmatic Energy Sector Development Policy Credit. [Accessed: July 5, 2019]. Available at: http://documents.worldbank.org/curated/en/104141537500644401/pdf/Nepal-Energy-DPC-Program-Document-08272018.pdf

World Bank. 2018. DataBank-online tool for visualization and analysis. [Accessed: July 8, 2019]. Available at: https://data.worldbank.org/indicator/EN.ATM.CO2E.SF.KT?locations=NP&view=map

World Bank. 2020. Kenya: Off-grid solar access project for undeserved counties. [Accessed: April 7, 2020]. Available at: https://projects.worldbank.org/en/projects-operations/project-detail/P160009

World Health Organization. 2018. Household air pollution and health: Key Facts. [Accessed: November 30, 2018] Available at: https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

World Health Organization. 2018. Opportunities for transition to clean household energy: application of the Household Energy Assessment Rapid Tool (HEART) in India. Geneva: World Health Organization; 2018. Licence: CC BY-NC-SA 3.0 IGO. [Accessed: July 12, 2019] Available at: https://apps.who.int/iris/bitstream/handle/10665/274280/9789241513999-eng.pdf;jsessionid=9268070F01258B76703BEF64E904EC50?sequence=1

World Health Organization. 2019. Kathmandu to mitigate air pollution with UHI: First in Asia. [Accessed: July 5, 2019]. Available at: http://www.searo.who.int/nepal/documents/environment/UHI_Feb_2019/en/

Worldometers. 2018. [Accessed: April 12, 2020]. Available at: http://www.worldometers.info/world-population/kenya-population/

Wu, X., Jeuland, M., Sadoff, C., & Whittington, D. (2013). Interdependence in water resource development in the Ganges: an economic analysis. *Water Policy*, *15*(S1), 89-108

Yale University 2018. 2018 Environmental Performance Index. New Haven, CT: Yale University. [Accessed: October 22, 2018]. Available: https://epi.envirocenter.yale.edu/2018-epi-report/air-quality

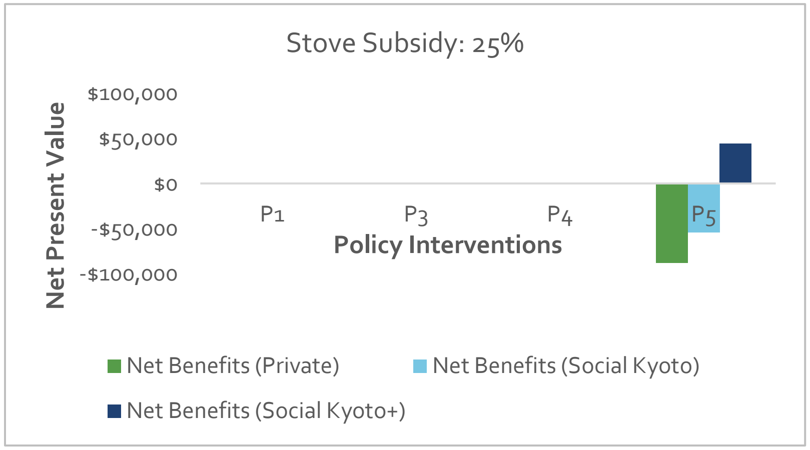
Zhang, J. and Smith, K.R., 1999. Emissions of carbonyl compounds from various cookstoves in China. *Environmental Science & Technology*, *33*(14), pp.2311-2320.

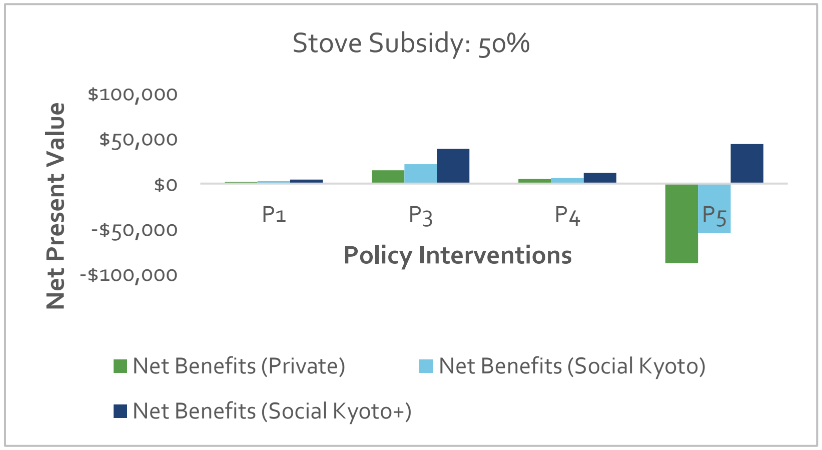
Zhou, Z., Dionisio, K. L., Verissimo, T. G., Kerr, A. S., Coull, B., Arku, R. E., ... & Agyei-Mensah, S. 2013. Chemical composition and sources of particle pollution in affluent and poor neighborhoods of Accra, Ghana. *Environmental Research Letters*, *8*(4), 044025.

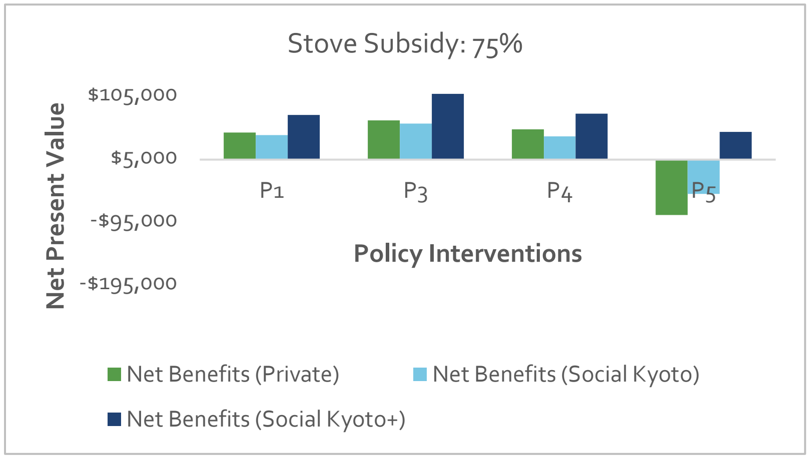
Supplementary Appendices

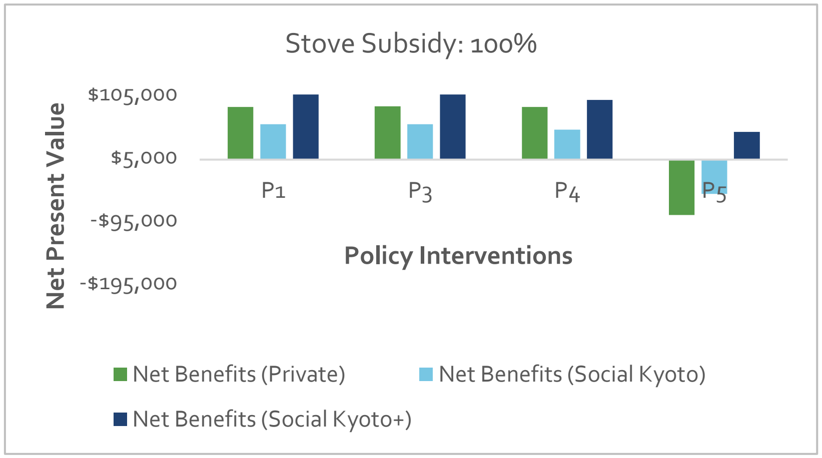
Appendix A – Additional Figures

Transition 1 (Traditional charcoal to ICS charcoal)









Appendix A1. Net benefits after varying stove subsidy levels for Nairobi – Transition 1 (Traditional charcoal to ICS charcoal). P1-P5 stand for policy interventions: stove subsidy (P1), stove financing with stove subsidy (P3), BCC with stove subsidy (P4) and polluting fuel ban (P5).

Transition 2 (All charcoal stoves to LPG)

Appendix A2. Net benefits after varying stove subsidy levels for Nairobi – Transition 2 (All charcoal stoves to LPG). P1-P5 stand for policy interventions: stove subsidy (P1), fuel subsidy with stove subsidy (P2), stove financing with stove subsidy (P3), BCC with stove subsidy (P4) and polluting fuel ban (P5).

Transition 3 (Kerosene stoves to LPG)

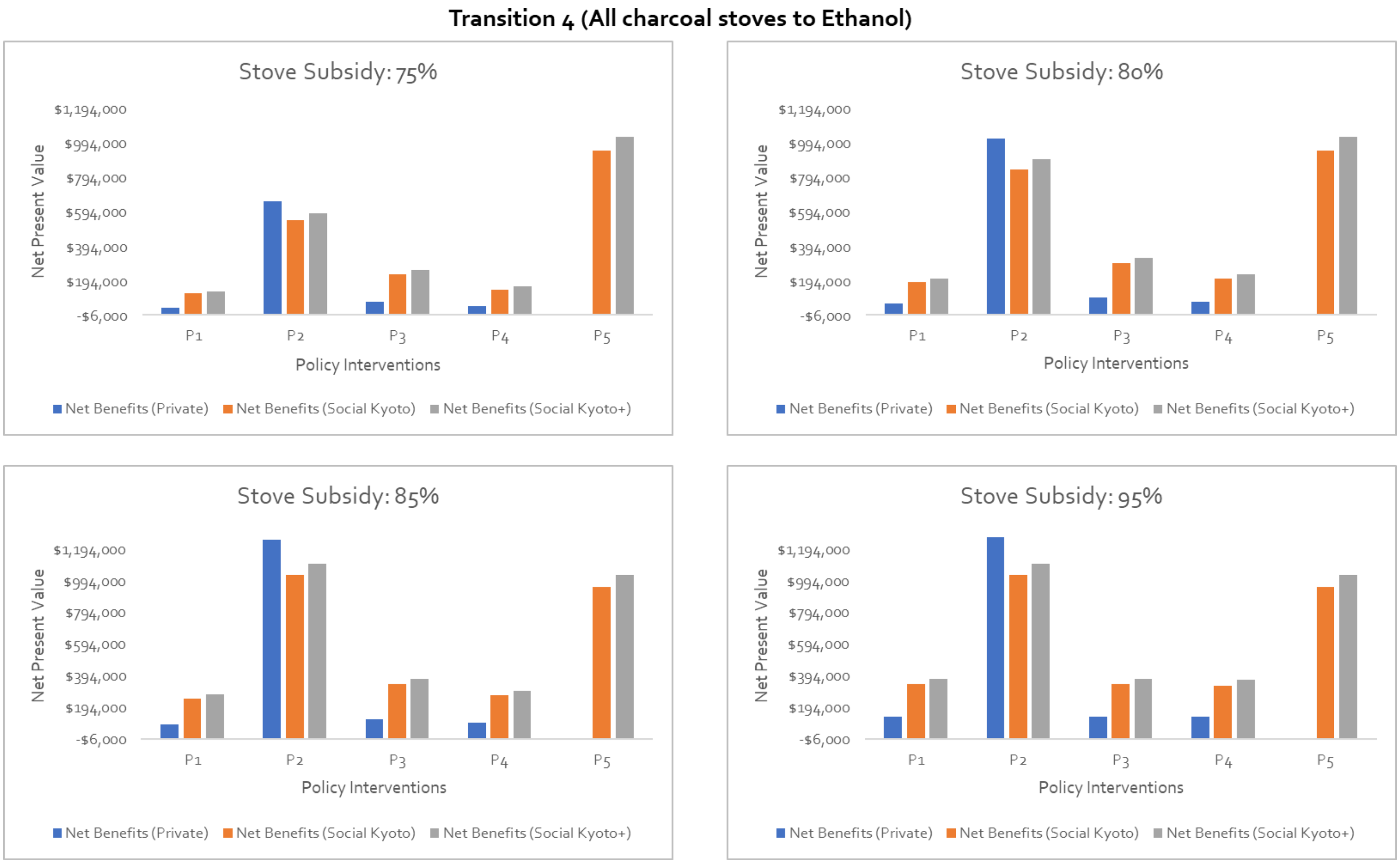

Stove Subsidy: 80%

Stove Subsidy: 85%

Stove Subsidy: 90%

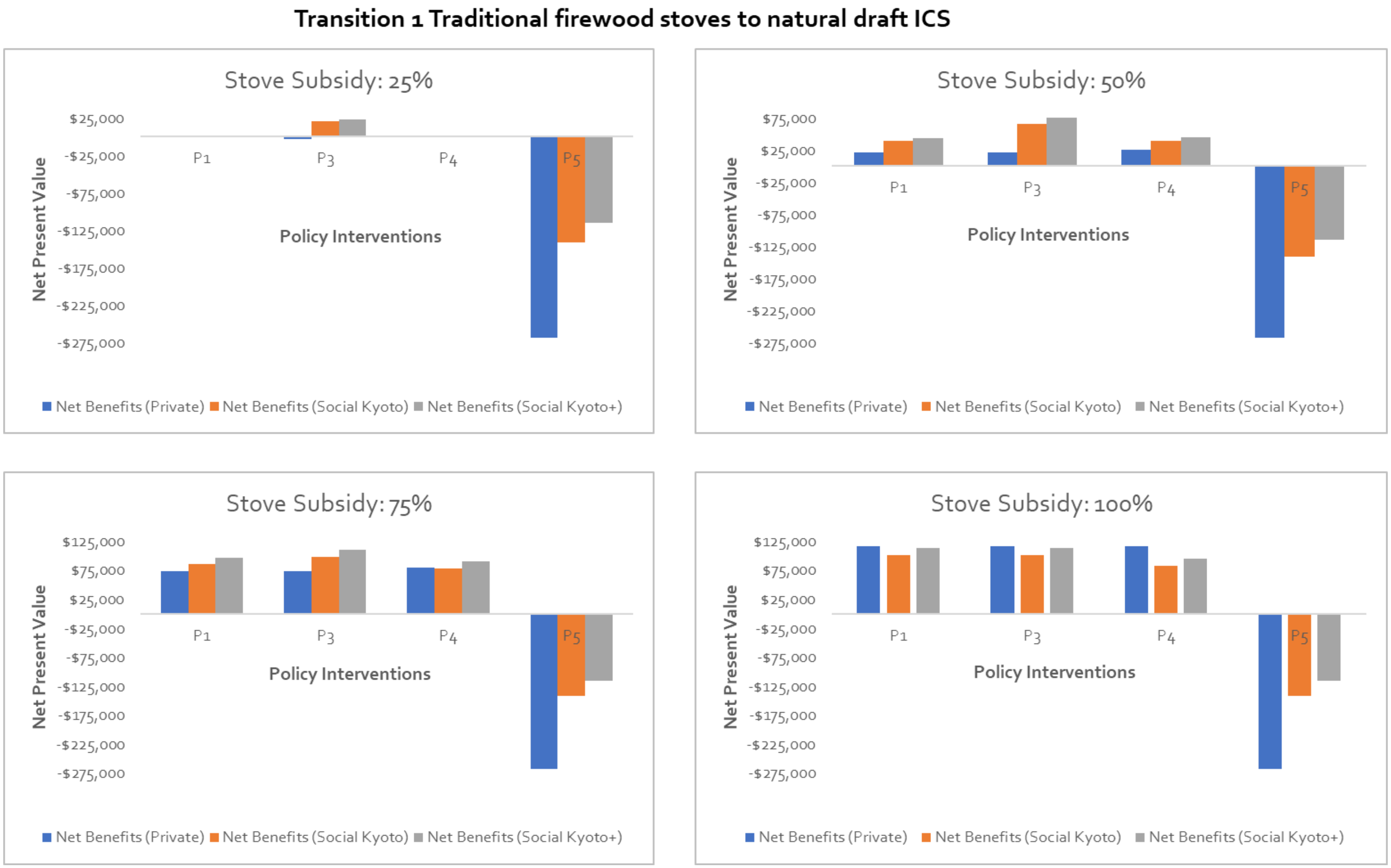
Stove Subsidy: 95%

Appendix A3. Net benefits after varying stove subsidy levels for Nairobi – Transition 3 (Kerosene stoves to LPG). P1-P5 stand for policy interventions: stove subsidy (P1), fuel subsidy with stove subsidy (P2), stove financing with stove subsidy (P3), BCC with stove subsidy (P4) and polluting fuel ban (P5).



Appendix A4. Net benefits after varying stove subsidy levels for Nairobi – Transition 4 (All charcoal stoves to Ethanol). P1-P5 stand for policy interventions: stove subsidy (P1), fuel subsidy with stove subsidy (P2), stove financing with stove subsidy (P3), BCC with stove subsidy (P4) and polluting fuel ban (P5).

Appendix A5. Net benefits after varying stove subsidy levels for Nairobi – Transition 5 (Kerosene stoves to Ethanol). P1-P5 stand for policy interventions: stove subsidy (P1), fuel subsidy with stove subsidy (P2), stove financing with stove subsidy (P3), BCC with stove subsidy (P4) and polluting fuel ban (P5).



Appendix A6. Net benefits after varying stove subsidy levels for Kathmandu Valley – Transition 1 (Traditional firewood stoves to natural draft ICS). P1 – P5 stand for policy interventions: stove subsidy (P1); stove financing w/ stove subsidy (P3); BCC w/ stove subsidy (P4) and technology ban (P5).

Transition 2 Traditional firewood stoves to LPG

Appendix A7. Net benefits after varying stove subsidy levels for Kathmandu Valley – Transition 2 (Traditional firewood stoves to LPG). P1 – P5 stand for policy interventions: stove subsidy (P1); fuel subsidy w/ stove subsidy (P2); stove financing w/ stove subsidy (P3); BCC w/ stove subsidy (P4) and technology ban (P5).

Transition 3 Traditional firewood stoves to Electric stoves

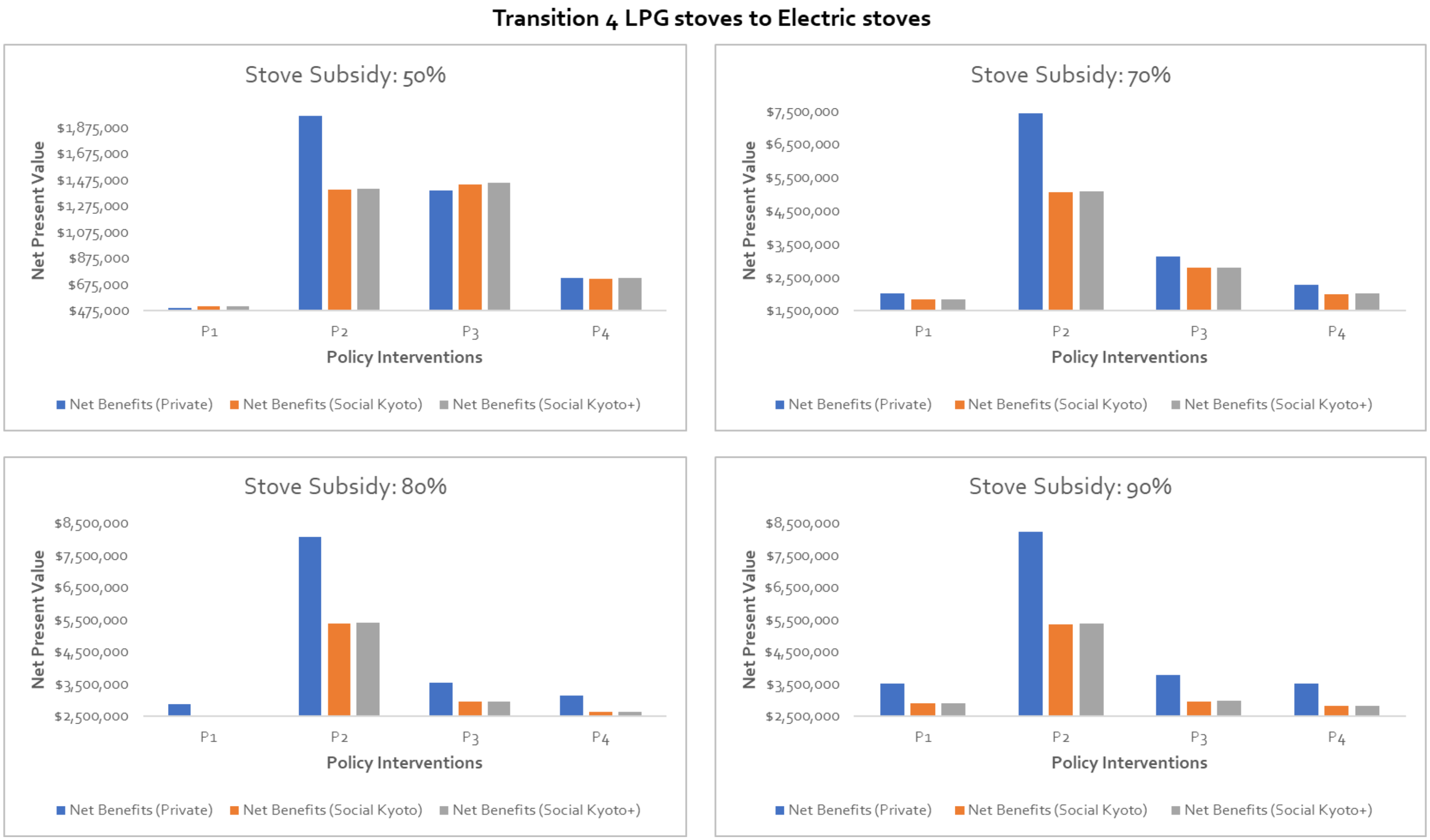
Stove Subsidy: 80%

Stove Subsidy: 85%

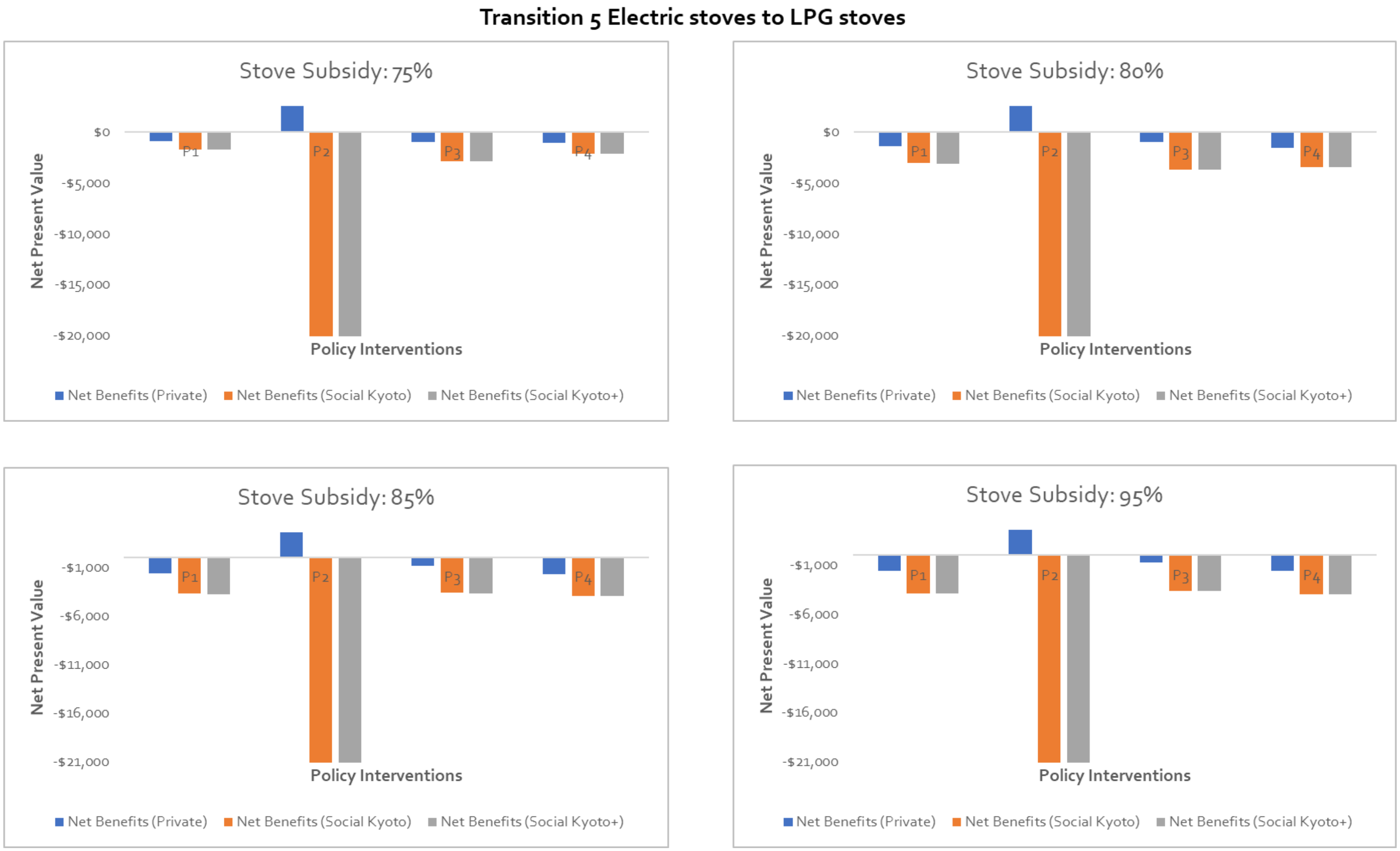
Stove Subsidy: 90%

Stove Subsidy: 95%

Appendix A8. Net benefits after varying stove subsidy levels for Kathmandu Valley – Transition 3 (Traditional firewood stoves to electric stoves). P1 – P5 stand for policy interventions: stove subsidy (P1); fuel subsidy w/ stove subsidy (P2); stove financing w/ stove subsidy (P3); BCC w/ stove subsidy (P4) and technology ban (P5).



Appendix A9. Net benefits after varying stove subsidy levels for Kathmandu Valley – Transition 4 (LPG stoves to electric stoves). P1 – P5 stand for policy interventions: stove subsidy (P1); fuel subsidy w/ stove subsidy (P2); stove financing w/ stove subsidy (P3); BCC w/ stove subsidy (P4) and technology ban (P5).



Appendix A10. Net benefits after varying stove subsidy levels for Kathmandu Valley – Transition 5 (Electric stoves to LPG stoves). P1 – P5 stand for policy interventions: stove subsidy (P1); fuel subsidy w/ stove subsidy (P2); stove financing w/ stove subsidy (P3); BCC w/ stove subsidy (P4) and technology ban (P5).

Appendix B1. Description of clean cooking stakeholder agencies in Kenya.

Name	Description
A. Public Sector Agencies	
Kenya Bureau of Standards (KEBS)	This government agency (a) provides Standards, Metrology and Conformity Assessment services; (b) provides facilities for the testing and calibration of precision instruments; (c) facilitates examination and testing of commodities; and (d) transfers knowledge to small enterprises.
Ministry of Energy (MoE)	This Ministry's Energy Act 2019 (previously Energy Bill 2017) mandates each county government to develop and submit its own energy plan. The Energy Policy Country Action Plan with SE4All (spanning 2015-2030) also falls under this Ministry. This plan aims to achieve universal access to modern energy services (electricity access by 2022 & access to modern cooking solutions by 2028), increase the rate of energy efficiency and increase to 80% the share of renewable energy in the energy mix by 2030.
Energy and Petroleum Regulatory Authority (EPRA)	Established under the Energy Act 2006, among other objectives, it aims to (a) regulate electrical energy, petroleum, renewable energy and other energy forms; (b) ensure that principles of fair competition in the energy sector are implemented. Regarding LPG, the EPRA is concerned with safety, testing of cracks in cylinders, regulation and licensing of LPG dealers, but does not deal with pricing of LPG, unless buying from National Oil Corporation (the government's biggest LPG supplier).
Rural Electrification and Renewable Energy Corporation	Formed under the Energy Bill 2017, along with other agencies, this agency will develop and promote the use of renewable energy and technologies (e.g., biomass, biodiesel, bio-ethanol, charcoal, fuelwood, solar, wind, tidal waves, small hydropower, biogas, co-generation and municipal waste) except geothermal energy.
Ministry of Environment and Forestry (MoEF)	This Ministry leads Kenya's National Climate Change Action Plan (2018-2022), which prioritizes electricity supply from renewable energy and encourages transition to clean cooking. The Forest (Charcoal) Regulations 2009 and 2018 gazette notice on charcoal production, burning and trade were also issued by this Ministry.
Ministry of Health (MoH)	The Ministry has included household air pollution in the 5-year (2018-2022) universal coverage policy that seeks to ensure everyone has access to quality and affordable health. It also plans to develop strategies, manuals, and a curriculum for training community health volunteers and extension workers.
Ministry of Industry, Trade and Cooperatives (MoITC)	Among its many functions, this Ministry is responsible for (a) industrialization and cooperation policy formulation and implementation, (b) private sector development and strategy, (c) development of micro, small and medium enterprises and (d) the 'Buy Kenyan Build Kenya' policy (aimed at job creation and supporting development of Kenya's competitive manufacturing sector).
Kenya Industrial Research and Development Institute (KIRDI)	This government body has the mandate to conduct research and development in industrial and allied technologies, including environment and energy, among others. Technologies thus developed are transferred to micro-, small- and medium enterprises and large industries. KIRDI develops and uses test protocol for improved cookstoves and provides stove performance ratings.

B. Private Sector Agencies/Companies	
Burn Manufacturing	Sub-Saharan Africa's only local improved cookstoves manufacturing company (based in Kenya) designs, produces and distributes charcoal (*Jikokoa*) and wood (*Kuniokoa*) improved cookstoves.
BioLite	It designs, manufactures and sells energy products for off-grid communities globally. In developing countries, their geographical focus is in East Africa and India where they sell the BioLite HomeStove (improved wood stove).
Cookswell Jiko	Based in Nairobi, this family-owned business designed the first energy-saving *Jiko* (Kenya Ceramic *Jiko*) and now trains artisans to manufacture the same. They distribute cookstoves to the East African market as well. Artisanal improved charcoal stoves (without the Cookswell stamped liner) available in the Kenyan market are replicas of the KCJ.
EcoZoom	Headquartered in Nairobi, Kenya, this social enterprise delivers improved cookstoves and solar lighting solutions in the country. Charcoal stoves available include *Jiko Makaa*, *Jiko Bora Mama Yao (Makaa)* and *Jiko Fresh (Makaa)*; and *Jiko Dura (Kuni)* is their wood stove.
Envirofit International	This social enterprise develops improved cooking technologies for emerging and underdeveloped markets. Envirofit Kenya assembles improved cookstoves in Nairobi and distributes them locally and to other East African countries including Mozambique, Rwanda, Tanzania, Uganda and Zambia. Charcoal improved cookstoves sold in Kenya include SuperSaver Charcoal, SmartSaver Charcoal, and wood improved cookstoves include SuperSaver Wood and Econofire. Envirofit's new LPG technology service, SmartGas, is targeted to informal settlements in urban areas to provide safe and convenient delivery of LPG and pay-as-you-cook LPG purchases (i.e. ability to pay for smaller quantities). Its SmartValve technology uses mobile communication systems to notify refill requirements.
Kenya Association of Manufacturers (KAM)	This represents the manufacturing value-add industries, promoting trade and investment and facilitating policies around building a competitive business environment. Along with MoITC, KAM petitioned for import taxes to be increased on improved cookstoves, to encourage local manufacturing and employment
KOKO Networks	A venture capital-funded technology company, it builds and installs ethanol retail points inside local stores in urban areas in Kenya and Uganda, in partnership with major consumer goods suppliers.
Petroleum Institute of East Africa (PIEA)	As the oil and gas industry's professional body in the East African region, among its core objectives include lobbying with policy makers and regulatory agencies for providing a legal, stable and fair market. Along with CCAK and EPRA, PIEA lobbied for increase in kerosene price (anti-adulteration levy) and reduction in LPG price.
C. Development Sector Organizations & Donor Agencies	
Clean Cooking Association of Kenya (CCAK)	A local alliance of all actors in the clean cooking sector in Kenya, supported by the Clean Cooking Alliance, USA and key development sector partners such as SNV, GIZ-EnDeV and Hivos, among others.
Equity Foundation	The corporate social responsibility division of the Equity Bank Group provides the EcoMoto Loan to allow customers to access clean cooking and lighting solutions conveniently and under attractive financing conditions.

GIZ Energy	This is an Energy Initiative between 6 donor countries that started in 2006 with the aim of sustainable energy access. In Kenya, the focus is on clean cooking and lighting in rural areas, primarily to understand supply constraints, consumer needs and education, stove quality and marketing. It has results-based financing programs for improved stoves, solar lighting and mini-grids (the latter two led by GIZ Energy/EnDev).
SNV	In Kenya, its long-standing involvement has been in biogas programs in rural areas (with Hivos), but now implements the clean cookstoves component for GIZ Energy's results-based financing programs and KOSAP as a Facility Manager.
United Nations Environment Program (UNEP)	Though not an active player in the clean cooking domain, it focuses on affordable air quality monitoring, supports Kenya's development of policies around air quality improvement and develops public awareness programs.

Figure B1. Clean cooking sector stakeholders in Kenya

A. Public Sector Agencies

1. Ministry of Energy (MoE)
    - Energy and Petroleum Regulatory Authority (EPRA)
    - Rural Electrification and Renewable Energy Corporation
    - Renewable Energy Resource Advisory Committee
2. Ministry of Environment and Forestry (MoEF)
3. Ministry of Health (MoH)
4. Ministry of Industry, Trade and Cooperatives
    - Kenya Industrial Research and Development Institute (KIRDI)
    - Kenya Bureau of Standards (KEBS)

B. Private Sector Agencies

1. Burn Manufacturing
2. BioLite
3. Cookswell Jikos
4. EcoZoom
4. Envirofit
5. Kenya Association of Manufacturers
6. KOKO Networks
7. Petroleum Institute of East Africa (PIEA)

C. Development Sector Organizations & Donor Agencies

1. Clean Cooking Association of Kenya (CCAK)
2. Equity Foundation
3. GIZ Energy
4. SNV
5. United Nations Environment Program (UNEP)
6. Practical Action
7. Hivos

Appendix B2. Description of clean cooking stakeholder agencies in Nepal

Name	Description
A. Public Sector Agencies	
Ministry of Commerce and Supply	This ministry’s main task is to create, implement and monitor policies, plans and programs within domains of industry, commerce and supplies to promote Nepal’s international trade and industrial development.
Nepal Oil Corporation (NOC)	Founded in 1970, this state-owned enterprise imports, transports, stores and distributes petroleum products in Nepal, including petrol, diesel, kerosene, LPG and aviation turbine fuel. Indian Oil Corporation is its largest supplier of petroleum products.
Ministry of Energy, Water Resources and Irrigation	Three key departments operate under this Ministry of Energy, Water Resources and Irrigation, -Department of Water Resources and Irrigation, Department of Electricity Development and Department of Hydrology and Meteorology.
Alternative Energy Promotion Center (AEPC)	The Government of Nepal established this agency in 1996 to promote the effective and efficient use of renewable energy. It provides technical and financial assistance for biomass energy promotion, in partnership and collaboration with the private sector, NGOs, and local communities. And energy efficiency
Nepal Electricity Authority (NEA)	This is the country’s central authority for grid electricity supply, established in 1985 under the Nepal Electricity Authority Act 1984 by merging numerous institutions involved in electricity generation, transmission and distribution. NEA operate under this Ministry of Energy, Water Resources and Irrigation,
Renewable Energy Test Station (RETS)	This autonomous body governed by “Renewable Energy Test Station Rules 2063” is Nepal’s foremost laboratory for testing solar photovoltaic components, measurement of solar home systems’ quality, efficiency of ICS, solar dryers, solar cookers among other renewable energy devices.
B. Non-governmental Organizations & Private Sector Agencies	
Ajummery Bikas Foundation (ABF)	This is a private company established in 2013, initially to promote a supply chain for rocket ICS involving women entrepreneurs and microfinance institutions. It is now leading an electric stoves campaign targeting 3,000 households across 52 districts and is considered a supply-side development partner developing and linking local suppliers to bigger, national suppliers.
Center for Rural Technology-Nepal (CRT-N)	Started about 20 years ago with support from SNV, this NGO is a regional cookstove testing center with its own lab.
Clean Air Network Nepal (CANN)	Formed in 2004, this country network of the international NGO Clean Air Asia, aims at establishing a collaborative network of relevant stakeholders working on air pollution problems in Nepal. It comprises individuals, experts, local and international NGOs, government agencies and the private sector involved in clean air activities.
Himalayan Naturals	This NGO started in 2009 to provide an urban market for rural communities in Nepal, by promoting biomass briquettes. Operational in about 10 districts, communities have a 10% shareholding in the company.

Husk Power Nepal Pvt. Ltd.	The company was established in 2012 and to-date has delivered more than 1,13,000 Tier II ICS-considered one of the best stoves in the Nepal market in terms of fuel efficiency and emissions reduction. They recently launched their Tier-III ICS (41.24% thermal efficiency). The company also manufactures woodchips and imports and supplies solar panels and its accessories for solar home systems, institutional systems and solar lifting for irrigation.
Nepal Energy Foundation (NEF)	Founded in 2015, this non-profit company promotes sustainable energy solutions in Nepal. They aim to provide inputs for effective policy formulation, address bottlenecks in clean energy implementation (e.g. finance, productive use, benefit sharing, and knowledge and capacity building), and encourage energy security.
C. International NGOs & Donor Agencies	
Asian Development Bank (ADB)	Nepal's leading power sector partner provides on-grid support for NEA's expansion of generation, transmission and distribution capacity. Support is also provided for small hydropower projects, community-centered rural electrification projects and helping NEA with financial restructuring and tariff increase.
GIZ Endev	An energy initiative between 6 donor countries started in 2006 with the aim of sustainable energy access. In Nepal, it has been operating programs for the past 12 years. It has sub-contracted projects to Practical Action, and is only involved in quality control, as part of its results-based financing program.
International Center for Integrated Mountain Development (ICIMOD)	An intergovernmental center for learning and knowledge sharing in the South and South-East Asian region, its Atmosphere Program, started in 2013, seeks to improve understanding of the air pollution problem in the region, and identify solutions.
Practical Action	In Nepal, this international NGO has projects on energy access; agriculture and food security; urban water, waste and sanitation; and disaster risk reduction. Within the energy access portfolio, it is focused on increasing the private sector's participation in the energy access market and generating demand for clean energy products and services in remote, marginalized communities.
World Health Organization (WHO)	On air pollution, WHO's main project in Nepal is the Urban Health Initiative. Kathmandu is the first city in Asia where this initiative's model approach will be adapted (Accra, Ghana was the first city globally to initiate UHI's approach).

Figure B2. Clean cooking sector stakeholders in Nepal

A. Public Sector Agencies

1. Ministry of Commerce and Supply
    - ❖ National Oil Corporation (NOC)
2. Ministry of Energy, Water Resources and Irrigation
    - ❖ Alternative Energy Promotion Center (AEPC)
    - ❖ Nepal Electricity Authority (NEA)
3. Ministry of Forests & Environment
4. Ministry of Education, Science & Technology
    - ❖ Renewable Energy Test Station (RETS)
5. Ministry of Health & Population

B. Non-governmental Organizations & Private Sector Agencies

1. Ajummery Bikas Foundation (ABF)
2. Center for Rural Technology-Nepal (CRT-N)
3. Clean Air Asia
4. Himalayan Naturals
5. Husk Power Nepal Pvt. Ltd.
6. Nepal Energy Foundation

C. International NGOs & Donor Agencies

1. Asian Development Bank (ADB)
2. GIZ (Endev, RERA)
3. International Center for Integrated Mountain Development (ICIMOD)
4. Practical Action
5. World Health Organization (WHO)
6. World Bank

Appendix C. Equations for calculations

Costs

1. Stove cost

Stove capital cost (*Cap*) is calculated by amortizing the cost of clean cooking (c_i^m) over its lifetime in years (T_i) and the discount rate (δ_p for private; δ_s for social), using the capital recovery factor (*crf*). A monthly cost is obtained by dividing this annualized cost by 12. The term s^c refers to the capital cost subsidy, which reduces only private capital costs (not social costs).

$Cap = SW \cdot ({}^{s^c \cdot c_i^m \cdot crf}/_{12})$, where SW= number of improved/clean cooking option switchers in Nairobi City (C1)

$$crf = {}^{\delta \cdot (1+\delta)^T}/_{(1+\delta)^T - 1} \cdot \qquad \text{(C2)}$$

This cost applies only to adopters. For existing improved/clean cooking users and non-adopters, this cost is $0. The fraction of Nairobi city's households in the 'switcher' category can be calculated by (i) deriving a price-demand relationship either based on the price elasticity of demand estimates from the literature, or by making assumptions of the demand curve using different elasticities; (ii) making assumptions about the switchers group through less structural methods; or (iii) basing values from empirical studies.

2. Program cost

The program cost (*Prog*) is the cost to the Nairobi city government of implementing a clean cooking energy program. These include costs of clean cooking procurement, delivery, marketing and promotion material, government staff time. The annual program cost (c^p) is divided by 12 to obtain a monthly cost.

$$Prog = SW \cdot {}^{c^p}/_{12} \qquad \text{(C3)}$$

3. Operation and maintenance cost

Net operation and maintenance cost (*O&M)* are the difference between the maintenance cost of clean cooking option (*Main*$_i$) and that of a baseline stove (*Main*$_0$). The cost of maintenance for a traditional charcoal stove is assumed to be zero as these stoves are easily replaced and typically much cheaper compared to their clean cooking counterparts. On the other hand, while it has been well-documented that regular maintenance is essential for continuing clean energy usage, very few studies collected data on maintenance cost. To this end, we estimate the clean cooking option's monthly maintenance cost by amortizing a *variable* fraction of the stove's cost by its lifetime.[36] Finally, we scale the difference in maintenance cost by the rate of usage (χ) of the clean cooking intervention as a lower rate of usage would indicate a reduced need for regular upkeep.

---

[36] In lieu of actual data on stoves' maintenance cost, we proxy by amortizing a fraction of stove's purchase cost where this fraction ranges from 50% to 100% of the stove's cost.

$$O\&M = TotalPopn \cdot [\chi_i \cdot \left(\frac{(Main_i - Main_0)}{12}\right)]$$, where TotalPopn = Nairobi's population (C4)

4. Learning cost

As with the stove purchase cost, we amortize the one-time learning cost (*l*, in hours) according to the lifetime (in years) of the clean cooking technology and divide by 12 to get a monthly cost. Since *l* is measured in hours, we need a valuation relationship for this time. To approximate the opportunity cost of time, we assume that the shadow value of time is some proportion (κ^t) of the unskilled wage rate (*W*). We rely on the national minimum wage rate as a guide for this unskilled wage rate. However, because this minimum wage probably overstates the value of time in locations with low rates of formal labor market participation, we additionally scale this official minimum wage rate by the shadow value of time parameter (κ^t) that represents the opportunity cost of time as a fraction of this minimum wage.

$$Learn = SW \cdot ({}^{l \cdot v^t \cdot crf}/_{12})$$, where (C5)

$$v^t = \kappa^t \cdot W \quad \text{(C6)}$$

5. Fuel cost

Calculation of net monthly fuel savings (*Fuel*) due to a switch from a baseline stove technology to a clean cooking option requires several steps. The net value of fuel savings is calculated as the difference between the cost of clean cooking fuel used ($Fuelc_i$ in \$/month) and the cost of fuel used in a baseline stove ($Fuelc_0$). However, because most households may not use their improved/clean stove and fuel exclusively, we must weight these fuel savings by the improved/clean cooking usage rate χ:

$$Fuelsav = \chi_i \cdot (Fuelc_i - Fuelc_0) \quad \text{(C7)}$$

As fuel cost is not a commonly collected metric in surveys, we must find ways to approximate it using other data.

We first calculate $Fuelc_0$ (Equation B8):

$$Fuelc_0 = TotalPopn \cdot [(Fuelu_0 \cdot \ \chi_0 \ \cdot p_0)] \quad \text{(C8)}$$

The first term on the LHS is the cost of purchasing baseline fuel. This is derived by scaling fuel usage with the baseline stove ($Fuelu_0$ in kg/month) according to the time spent cooking on baseline technology and fuel spent cooking on the baseline technology per month. We note that this baseline fuel use in weight is not always reported by cookstove/clean cooking studies because it may be hard to measure or estimate. We can therefore approximate $Fuelu_0$ using equation B9:

$$Fuelu_0 = 30 \cdot (cook_0 \cdot fuelckg_0). \quad \text{(C9)}$$

In this expression, $Fuelu_0$ is obtained by multiplying the time spent cooking on a traditional charcoal stove ($cook_0$, in hr/day) by the amount of fuel used per hour of cooking ($fuelckg_0$).

The use of v^t in equations B5 and (later) B12 assumes that the value of cooking time, fuel collection time, and time spent learning to use an improved/clean cooking option is equivalent. We assume there is no fuel collection or preparation cost in calculating fuel costs in our transition scenarios, as we assume that the fuels under consideration (i.e. charcoal, kerosene, ethanol and LPG) do not need these.

Next, we calculate the improved/clean cooking fuel cost ($Fuelc_i$).

$$Fuelc_i = TotalPopn \cdot [Fuelu_i \cdot \chi_i \cdot (p_i + ft_i)] \tag{C10}$$

The term ft_i is used only for clean liquid fuel options (i.e. ethanol and LPG) wherein transport costs are incurred.

Finally, using information on the relative fuel efficiency of various cookstoves (εf_i) and energy content of different fuel types (μ_i, in MJ/kg), we can calculate the clean cooking option's fuel use ($Fuelu_i$) that is needed for the first term of equation A10:

$$Fuelu_i = Fuelu_0 \cdot {}^{\varepsilon f_0 \cdot \mu_0}\!/_{\varepsilon f_i \cdot \mu_i} \,. \tag{C11}$$

Benefits

6. Time savings

Equation (B5) values the time saved by cooking using an improved/clean cooking option relative to a baseline stove. Time saved is quantified by multiplying time spent cooking on a baseline stove ($time_0$ in hr/day) by the time efficiency of clean cooking option relative to a baseline stove (te_i). To arrive at a monthly figure that is indicative of usage (hr/month), we multiply the daily time savings by 30 (days) and by the rate of usage. Finally, we again value this time savings using the opportunity cost of time as defined above.

$$Timesav = TotalPopn \cdot [30 \cdot cook_0 \cdot \chi_i \cdot (1 - te_i)] \qquad \text{(C12)}$$

For the transition scenarios from improved charcoal stove to LPG stove and improved charcoal stove to ethanol stove, Equation (B12) above is modified to account for 50% traditional charcoal stove users switching and 50% ICS charcoal stove users switching to the clean stove option, as follows:

$$Timesav = TotalPopn \cdot [30 \cdot \chi_i \cdot (0.5 * cook_{ICS\ charcoal\ stove} * \ (1 - te_i)) + \big(0.5 * cook_{trad.charcoal\ stove} * \ (1 - te_i * te_{ICS\ charcoal\ stove}\ )\big)] \qquad \text{(C13)}$$

7. Health benefits

To value mortality and morbidity improvements from reduced exposure to household air pollution (HAP), we must first quantify health improvements. We use the exposure-response functions derived by Burnett et al (2014) for various respiratory-related diseases as they relate to concentrations of $PM_{2.5}$ (μg/m^3 in 24 hours). To calculate the level of $PM_{2.5}$ exposure following the clean cooking intervention ($PM_{2.5}$), we use data on emissions from different clean cooking stove options ($PM_{2.5,i}$) and scale the reductions from the baseline stove ($PM_{2.5,0}$) using the rate of the clean cooking option usage and also a pollution exposure adjustment parameter ε_i, which is meant to account for the behavioral response that may reduce exposure reductions due to cleaner cooking increasing individuals' contact time with harmful smoke:

$$\mathrm{PM}_{2.5} \ = \chi_i \cdot \varepsilon_i \cdot \mathrm{PM}_{2.5,i} + (1 - \chi_i) \cdot \varepsilon_0 \cdot \mathrm{PM}_{2.5,0} \qquad \text{(C14)}$$

Using this new concentration $\mathrm{PM}_{2.5}$, we use the Burnett relationship to calculate the relative risk (*RR*) of mortality (or morbidity) for specific diseases for each stove-fuel combination.[37] Because there are multiple causes for each disease, we must also assign the portion of risk attributable to stoves' emissions using the population attributable fraction (*PAF*). Calculation of the PAF for stove i (PAF_i) requires the fraction of population exposed to HAP and we use the proportion of solid fuel users (*sfu*) in the population as a proxy for this indicator (equation B15):

$$PAF_i = {}^{sfu * (RR_k - 1)}\Big/_{sfu * (RR_k - 1) + 1} \qquad \text{(C15)}$$

---

[37] Parameters for the relative risk functions can be downloaded from here: http://ghdx.healthdata.org/sites/default/files/record-attached-files/IHME_CRCurve_parameters.csv

Next, to quantify the reduction in mortality from a specific disease k (in the above relationship the following diseases are included: acute lower respiratory illness, chronic obstructive pulmonary disease, ischemic heart disease, and lung cancer) given the use of stove i, the change in the PAF is multiplied by the mortality rate of the disease MR_k. For morbidity improvements, we multiply the change in the PAF by the incidence rate (for ALRI) or prevalence rate (for other diseases) (IR_k).

$$Morb_k = hhsize \cdot (PAF_0 - PAF_i) \cdot IR_k \text{ and} \tag{C16}$$[38]

$$Mort_k = hhsize \cdot (PAF_0 - PAF_i) \cdot MR_k \tag{C17}$$

For valuing these benefits of reduced morbidity and mortality, we must account for the fact that the health improvements from HAP reductions are staggered in time by discounting those that occur in the future. To do this, we use the EPA's cessation lag concept, which assumes that 30% of the health benefits from HAP improvements are observed in the first year; 20% in the second year; and the remaining 50% are equally spread out over the next three years (Equations B18 and B19):

$$Morb = SW \cdot (1+\pi) \cdot \textstyle\sum_k (\sum_{t=1}^{5} CL_{kt} \cdot (Morb_k)/(1+\delta)^{t-1})/12, \tag{C18}$$

$$Mort = SW \cdot (1+\pi) \cdot \textstyle\sum_k (\sum_{t=1}^{5} CL_{kt} \cdot (Mort_k)/(1+\delta)^{t-1})\,/\,12, \tag{C19}$$

where CL_t=0.3 for t=1; 0.2 for t=2; and 0.5/3 for 3≤t≤5 for COPD; CL_t=0.7 for t=1; 0.1 for t=2; and 0.2/3 for 3≤t≤5 for ALRI; and CL_t=0.2 for t=1; 0.1 for t=2; and 0.7/3 for 3≤t≤5 for IHD and for LC. Finally, π represents a health spillovers factor that accounts for the reduction in morbidity and mortality from ambient air pollution due to reduced household biomass burning.

8. Climate-forcing emissions reductions

Climate-forcing emissions reductions constitute an important potential social benefit of more efficient cookstoves. Cooking with biomass in inefficient stoves produces a range of climate-forcing pollutants. As in the calculation of the economic benefits of health improvements, there are two main components in valuing reductions in these emissions (*Clim*) – the value of the (marginal) changes and the total amount of the reduction.

Calculating the amount of emissions reduction is complicated by the fact that cookstoves emit a range of pollutants, some of which (e.g., black carbon, CO, and CO_2) increase warming, and others of which (namely organic carbon) reduce it. These various emissions must be normalized and expressed in commensurate terms, at least with respect to the time-varying aspects of their overall global warming potential (*GWP*). Our approach builds on Shindell et al. (2015) to calculate the *GWP* due to cookstoves using base parameters for the global warming for the main substances these emit, which relates to the energy content of fuels and efficiencies of stoves.

We start by multiplying emissions factors $\varepsilon_{j,i}$ of particular gases j for various stove-fuel combinations i,m (e.g., $\varepsilon_{CO2,i,m}$ in g CO2-eq/MJ), by the GWP_j for those particular gases (GWP_{CO2}). Equation B20 shows the GWP_j derivation for a stove-fuel combination i that includes only the three greenhouse gases – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) – that were part of the Kyoto Protocol, and equation B21 is the one used in our analysis that generalizes this expression over additional pollutants (in our case this also includes black carbon (BC), organic

---

[38] For ALRI, we use the number of children under 5 (*hh<5*) instead of household size.

carbon (OC), non-methane hydrocarbons (NMHC), carbon monoxide (CO), and sulfur dioxide (SO_2). An important detail of this calculation is that the carbon dioxide component of GWP is multiplied by the fraction of non-renewable biomass ψ, since renewable harvesting sequesters carbon at the same rate as it is consumed (it does not affect net emissions). In addition, for charcoal emissions we include emissions produced during the charcoal production process.

$$GWP_{i,m,Kyoto} = \varepsilon_{CO2,i,m} \cdot \psi + \varepsilon_{N2O,i,m} \cdot GWP_{N20} + \varepsilon_{CH4,i,m} \cdot GWP_{CH4} \tag{C20}$$

$$GWP_{i,m} = \varepsilon_{CO2,i,m} \cdot \psi + \sum_{j\epsilon K} \varepsilon_{CO2,i,m} \cdot GWP_j, \text{ where } j = CO_2 \notin K \tag{C21}$$

For our purposes, the main challenge with the use of equation B21 is that the GWP of different pollutants changes over time in complex ways, since these substances have widely divergent lifetimes in the atmosphere. For example, CO_2 decays at a very slow rate and therefore exerts climate forcing over a long time horizon, while most of the climate forcing from BC is instantaneous. Climate scientists therefore typically compute an integral for GWP over some fixed time horizon *T* to express the forcing in commensurate terms. When used for valuation, this is equivalent to assuming that the discount rate δ over that fixed time horizon *T* is zero. There are thus two substantive problems with the approach: 1) It is incompatible with a world in which wealth is changing over time (which for equity purposes requires a non-constant discount factor), and 2) the assumed time horizon has a dramatic effect on the calculation of GWP, with no *a priori* rationale justifying the selection of a specific time horizon.

To address this issue, our approach derives the present value of radiative forcing associated with different pollutants. The formula for this calculation is shown in equation B22:

$$GWP_{j\epsilon K} = {\sum_{t=1}^{\infty} \frac{1}{(1+\delta_s)^{t-1}} \cdot RF_{j,t}} \Big/ {\sum_{t=1}^{\infty} \frac{1}{(1+\delta_s)^{t-1}} \cdot RF_{CO2,t}} \tag{C22}$$

where radiative forcing in future years is discounted relative to the present using an appropriate social discount rate δ_d, and still is normalized by the forcing from CO_2 (as shown in the denominator of B22). To obtain this time-discounted GWP, we simply calculate the time path of radiative forcing for pollutant *j* as a function of time *t* ($RF_{j,t}$ in W/m^2). For our purposes, we limit our time horizon to 100 years. We then substitute this pollutant-specific, time-normalized GWP into equation B21.

The final step is to compute the change in forcing following adoption of a different stove-fuel combination, and to value that change. This calculation is shown by equation B23.

$$Clim = TotalPopn \cdot \chi_i \cdot \left(fuelu_0 \cdot GWP_{i,m} \cdot \mu_m \cdot \varepsilon f_0 - fuelu_i \cdot GWP_{i,m} \cdot \mu_{i,m} \cdot \varepsilon f_i\right) \tag{C23}$$

In this expression, the CO_2-equivalent warming from stove *i* and fuel *m* ($GWP_{i,m}$ in g CO_2-eq/MJ useful energy) is multiplied by the energy content of the fuel being used (μ_m in MJ/kg fuel). This product is then multiplied by the fuel efficiency of the stove (εf_i) to account for differences in the thermal efficiency with which useful energy is derived from the fuel in a particular stove. This effective global warming potential (in g CO_2-eq/kg fuel) is then multiplied by the amount of fuel used per month ($fuelu_i$ in kg of fuel/month) to yield the g CO_2-eq/month. The terms for the traditional and improved ICS equivalent emissions are then scaled by the ICS usage rate.

9. Other environmental benefits

The other major category of social benefits is that related to the environmental services lost due to non-sustainable harvesting of biomass, or in the case of sustainable harvesting, the cost of tree replacement (*Bio*). The first type of such costs, associated with non-sustainable harvesting, is very difficult to generalize, and there are few high-quality studies that measure such non-market values well. We can estimate the second category as the product of the cost of timber farming c^f (in $/kg of wood produced) multiplied by the change in renewably-harvested biomass (as previously estimated). This is clearly a lower bound for other environmental values since it does not include the value of avoided deforestation or forest degradation (except insofar as this contributes to global warming).

$$Bio = TotalPopn \cdot \chi_i \cdot (1-\psi) \cdot (fuelu_0 - fuelu_i) \tag{C24}$$

Appendix D. Parametrization of the model: Summary of data sources – Kenya Analysis

Table D1. Stove costs

Description	**Location**	**Value (in $)**	**Source**
<u>Traditional charcoal stove</u>			
Traditional metallic stove and Kenya Ceramic Jiko	Kenya	3.9	Kenya National Cooking Sector Study (2019)
<u>Improved charcoal stove</u>			
Envirofit charcoal stoves	Kenya	32-51	Envirofit Retail Price List (2018)
Jiko Okoa (Burn)	Kenya	39	Burn Manufacturing Website (2018)
Cookswell Jiko Ceramic Stove	Kenya	6.9-9.8	Cookswell Jiko Website (2018)
Statistics – Mean (SD)		**29.9 (18.3)**	
<u>Kerosene stove</u>			
Kerosene wick stove	Kenya	4.9	Kenya National Cooking Sector Study (2019)
<u>LPG stove</u>			
Average of Meko, LPG multiple burner	Kenya	61.1	Kenya National Cooking Sector Study (2019)
<u>Ethanol stove</u>			
SAFI domestic 2-burner stove	Kenya	50-70	Dalberg Report (2018)
Koko Network 2-burner stove	Kenya	45	Dalberg Report (2018)
Koko Network 1-burner stove	Kenya	30	Dalberg Report (2018)
Statistics – Mean (SD)		**45.0 (15.0)**	

Notes: For statistical computation, we use the median values for stoves with ranges of costs.

Table D2. Program costs (c^p, in $/hh-yr)

Description	**Location**	**Value**	**Source**
<u>Expert estimates</u>			
Transitional and clean stoves	Global	17.0	WHO BAR-HAP Tool (2020)

Table D3. Maintenance costs (per year)

Description	Location	Value (in $)	Source
<u>Charcoal ICS</u>			
Briketi	Uganda	1.0	Clean Cooking Catalogue; 50% dep. assumption
Canamake	Rwanda	0.7	Clean Cooking Catalogue; 50% dep. assumption
Charcoal stove	China	3.3	Clean Cooking Catalogue; 50% dep. assumption
Statistics – Mean (SD)		**1.7 (1.4)**	
<u>Kerosene stove</u>			
Kerosene stove	Nepal	0.4	Pokharel (2004)
Kerosene stove	Nepal	1.1	Pokharel (2004); 50% dep. assumption
Statistics – Mean (SD)		**0.8 (0.5)**	
<u>LPG stove</u>			
LPG	Nepal	0.5	Pokharel (2004)
NG 4B SS	Mexico	4.3	Clean Cooking Catalogue; 50% dep. assumption
NG 4B	Mexico	4.0	Clean Cooking Catalogue; 50% dep. assumption
NG 2B	Mexico	2.0	Clean Cooking Catalogue; 50% dep. assumption
NG 2B gas	Mexico	2.1	Clean Cooking Catalogue; 50% dep. assumption
NG 2B SS	Mexico	2.0	Clean Cooking Catalogue; 50% dep. assumption
LPG	Nepal	0.5	Pokharel (2004); 50% dep. Assumption
LPG stove Telia	Burkina Faso	4.2	Clean Cooking Catalogue; 50% dep. assumption
Statistics – Mean (SD)		**2.6 (1.4)**	

Table D4. Lifespan of stove (T_i, in years)

Description	Location	Value	Source
Traditional charcoal stove			
Traditional Jiko	Kenya	1-2	Bailis et al. (2005)
Traditional Jiko	Kenya	1	Hyman (1987)
Statistics – Mean (SD)		**4.4 (3.3)**	
Charcoal ICS			
Briketi EcoStove	Uganda	5	Clean Cooking Catalog
Briketi EcoStove v2	Uganda	5	Clean Cooking Catalog
Canamake Ivuguruye	Rwanda	4	Clean Cooking Catalog
Burkina Mixte	Burkina Faso	2	Clean Cooking Catalog
Charcoal Jambar	Africa	2	Clean Cooking Catalog
CookClean CookMate	Ghana	4	Clean Cooking Catalog
EcoRecho	Haiti	1	Clean Cooking Catalog
Hifadhi	Kenya	5	Clean Cooking Catalog
Improved Canamake	Rwanda	4	Clean Cooking Catalog
Ã‰clair		2	Clean Cooking Catalog
EzyChar		3	Clean Cooking Catalog
Firewood Stove		15	Clean Cooking Catalog
Jiko Africa		2	Clean Cooking Catalog
JikoJoy		5	Clean Cooking Catalog
jikokoa		2	Clean Cooking Catalog
Jiko Smart Charcoal		5	Clean Cooking Catalog
Kunimbili		4	Clean Cooking Catalog
KuniTatu - Three Stick Stove		2	Clean Cooking Catalog
Mbaula Green		4	Clean Cooking Catalog
MBS 9		15	Clean Cooking Catalog
Multimarmite		2	Clean Cooking Catalog
Nansu Unfired Clay		1	Clean Cooking Catalog
Obama Stove		3	Clean Cooking Catalog
Okelo Kuc		3	Clean Cooking Catalog
Original Gyapa		3	Clean Cooking Catalog
Peko Pe		10	Clean Cooking Catalog
Portico Premium Stove		3	Clean Cooking Catalog
Rahisi Stove (Prototype)		10	Clean Cooking Catalog
Rapidita		4	Clean Cooking Catalog
Recho Plop Plop+		2	Clean Cooking Catalog
Rocket Works Cha-ZaMa Charcoal Stove		1	Clean Cooking Catalog
Rua		3	Clean Cooking Catalog
Sakkanal		2	Clean Cooking Catalog
SCODE charcoal stove all metal		7	Clean Cooking Catalog
SCODE Push-n-Pull stove		6	Clean Cooking Catalog
SCODE SP-FL micro gasifier Concrete body		5	Clean Cooking Catalog

SCODE SP-FL micro gasifier portable		5	Clean Cooking Catalog
SmartHome Stove		2	Clean Cooking Catalog
Zoom Stove		3	Clean Cooking Catalog
Zoom Versa		5	Clean Cooking Catalog
Statistics – Mean (SD)		**4.4 (3.3)**	
<u>Kerosene</u>			
Kerosene	Nepal	3	Pokharel (2004)
<u>LPG</u>			
A1-m single stove	Ghana	4	Clean Cooking Catalog
NOMENA LPG Cookstove	Ghana	5	Clean Cooking Catalog
F2-m_Single stove	Ghana	4	Clean Cooking Catalog
LPG Stove Télia n°2	Burkina Faso	6	Clean Cooking Catalog
Moto Safi BG-02C	Kenya	8	Clean Cooking Catalog
Statistics – Mean (SD)		**5.4 (1.7)**	
<u>Ethanol</u>			
Moto Safi	Kenya	6	Clean Cooking Catalog
SAFI Cooker, Double Burner	Kenya, Madagascar, United Republic of Tanzania	5	Clean Cooking Catalog
SAFI Cooker, Single Burner	Kenya, Madagascar, United Republic of Tanzania	5	Clean Cooking Catalog
Statistics – Mean (SD)		**5.3 (0.6)**	

Table D5. Usage rate (χ)

Description	Location	Value	Source
Charcoal	Kenya (Nairobi)	5.5%	Kenya National Cooking Sector Study (2019)
Percentage using traditional charcoal stoves (metallic, KCJ)	Kenya (Nairobi)	82.5%	Duke Nairobi Survey (2019)
Percentage using improved charcoal stoves	Kenya (Nairobi)	17.5%	Duke Nairobi Survey (2019)
Kerosene	Kenya (Nairobi)	29.7%	Kenya National Cooking Sector Study (2019)
LPG	Kenya (Nairobi)	56.1%	Kenya National Cooking Sector Study (2019)
Ethanol	Kenya (Nairobi)	0.0%	Kenya National Cooking Sector Study (2019)

Table D6. Average daily cooking time with traditional stove ($cook_0$, in hr/day)

Description	Location	Value	Source
Traditional charcoal stove (metallic, KCJ)	Kenya (Nairobi)	1.5	Duke Nairobi Survey (2019)
Kerosene	Kenya (Nairobi)	1.3	Duke Nairobi Survey (2019)

Table D7. Time efficiency of ICS relative to traditional stove (*te_i*, as a ratio)

Description	Item	Value	Source
Charcoal ICS			
		1.02	Jetter et al. (2012)
		0.57	Jetter et al. (2012)
Statistics – Mean (SD)		**0.80 (0.32)**	
LPG			
		0.60	MacCarthy et al (2010)
		0.83	MacCarthy et al (2010)
Generic LPG	Rice	0.89	Houngan et al (2013)
Generic LPG	Beans	0.96	Houngan et al (2013)
Generic LPG	Dry corn	1.12	Houngan et al (2013)
Oryx LPG	Rice	0.77	Houngan et al (2013)
Oryx LPG	Beans	0.60	Houngan et al (2013)
Oryx LPG	Dry corn	0.93	Houngan et al (2013)
		0.53	Anozeia (2007)
Statistics – Mean (SD)		**0.8 (0.2)**	

Table D8. Thermal efficiency of stove (ϵf_i, in %)

Description	Details	Value	Source
Traditional charcoal			
Cambodia trad	Average thermal efficiency	14.5	Bhattacharya et al (2002)
Chinese trad	Average thermal efficiency	12.5	Bhattacharya et al (2002)
Thai bucket	Average thermal efficiency	16.2	Bhattacharya et al (2002)
Other stoves	Average thermal efficiency	30.8	Jeuland et al (2018)
Other stoves	Average thermal efficiency	23.9	Jeuland et al (2018)
Other stoves	Average thermal efficiency	37.7	Jeuland et al (2018)
Statistics – Mean (SD)		**22.6 (10)**	
Charcoal ICS			
Canamake	IWA high power efficiency	37.1	Clean Cooking Catalog
Obama Stove	IWA high power efficiency	34.0	Clean Cooking Catalog
Okelo Kuc	IWA high power efficiency	25.6	Clean Cooking Catalog
Okelo Kuc	Cold start efficiency	19.7	Clean Cooking Catalog
Okelo Kuc	Hot start efficiency	31.5	Clean Cooking Catalog
Okelo Kuc	Heating stove thermal efficiency	34.3	Clean Cooking Catalog
Okelo Kuc	Simmer efficiency	43.0	Clean Cooking Catalog
Kenya Ceramic Jiko	IWA high power efficiency	30.8	Clean Cooking Catalog
Kenya Ceramic Jiko	Cold start efficiency	23.9	Clean Cooking Catalog
Kenya Ceramic Jiko	Hot start efficiency	37.7	Clean Cooking Catalog
Envirofit	IWA high power efficiency	36.1	Clean Cooking Catalog
Burn Jikokoa	IWA high power efficiency	44.0	Clean Cooking Catalog
Burn Jikokoa	Cold start efficiency	44.0	Clean Cooking Catalog
Burn Jikokoa	Simmer efficiency	43.0	Clean Cooking Catalog
Statistics – Mean (SD)		**34.3 (7.5)**	
Kerosene			
Kerosene	Thermal efficiency	46.0	Anozie et al (2007)
Kerosene	Thermal efficiency	32.5	Dalberg Report (2018)
Statistics – Mean (SD)		**39.3 (9.5)**	
LPG			
LPG Stove Télia n°2	IWA high power efficiency	49.25	Clean Cooking Catalog
LPG Stove Télia n°2	Simmer efficiency	61.63	Clean Cooking Catalog
LPG Stove	Thermal efficiency	55	Dalberg Report (2018)
Statistics – Mean (SD)		**55.3 (6.2)**	
Ethanol			
Bio-ethanol stove	Thermal efficiency	60	Dalberg Report (2018)

Table D9. Calorific value (or fuel energy density) for stove (μ_i)

Description	Details	Value	Source
Charcoal		30	Jeuland et al. (2018)
Kerosene		43.5	IOR Energy[1]

LPG		48.3	IOR Energy[1]
Ethanol		29.6	IOR Energy[1]

[1] http://w.astro.berkeley.edu/~wright/fuel_energy.html

Table D10. Amount of fuel used for cooking; traditional stove ($fuelckg_0$, in kg/day)

Description	Location	Value	Source
Traditional charcoal	Kenya	0.95	Bailis (2003)
ICS	Kenya	0.63	Bailis (2003)

Table D11. Percentage of households buying baseline fuel (f)

Description	Location	Value	Source
Charcoal	Kenya (Nairobi)	5.5%	Kenya National Cooking Sector Study (2019)
Kerosene	Kenya (Nairobi)	29.7%	Kenya National Cooking Sector Study (2019)

Table D12. Average daily fuel procurement time ($collt_0$, in hr/day)

Description	Location	Value	Source
Charcoal	Kenya (Nairobi)	0.17	Duke Nairobi Survey (2019)
Kerosene	Kenya (Nairobi)	0.21	Duke Nairobi Survey (2019)
LPG	Kenya (Nairobi)	0.24	Duke Nairobi Survey (2019)

Table D13. Shadow value of time (fraction of wage) (κ^t)

Description	Location	Value	Source
Time spent obtaining cholera vaccines	Mozambique	0.35	Jeuland et al. (2010)
Value of time spent traveling – recent estimate	UK	0.33	Accent/Hague (1999), as cited in Mackie et al. (2002)
Value of time spent traveling – high estimate	UK	0.43	MVA, ITS, TSU (1987), as cited in Mackie et al. (2002)
Transport choices	UK	0.22	Quarmby (1967)

Transport choices	UK	0.45	Lisco (1968)
Choice of driving route	US	0.40	Thomas (1968)
Urban commuting choices	UK	0.22	Stopher (1969)
Choice of public transport alternatives	UK	0.3	Lee & Dalvie (1969)
Time spent collecting water	Kenya	1.2	Whittington et al. (1990)
Statistics – Mean (SD)		**0.43 (0.30)**	

Table D14. Minimum wage rates (*W*, in US$2015 per hr)

Country	Value
Kenya	0.25

Notes: Values obtained from https://en.wikipedia.org/wiki/List_of_minimum_wages_by_country.

Table D15. Average daily fuel preparation time for ICS stove (*prep*, in hr/day)

By assumption 0 hours (no data).

Table D16. Cost of fuel (p_i)

Description	Location	Value	Source
Charcoal ($/kg)	Kenya (Nairobi)	0.18	Duke Nairobi Survey (2019)
Kerosene ($/l)	Kenya (Nairobi)	1.02	Duke Nairobi Survey (2019)
LPG ($/kg)	Kenya (Nairobi)	1.34	Duke Nairobi Survey (2019)
Ethanol			
	Kenya	0.90	Dalberg Report (2018)
	Kenya	1.10	Dalberg Report (2018)
	Kenya	1.48	Dalberg Report (2018)
Statistics – Mean (SD)		**1.16 (0.29)**	

Table D17. Learning hours (*l*, in hours)

By assumption (no data)

Table D18. Incidence/prevalence of disease (IRk, in cases per 100 persons-yr)

Description	Location	Value	Source
<u>Acute lower respiratory infection</u>			
Incidence	Kenya	0.638	Smith & Mehta (2000)
<u>COPD</u>			
Prevalence	Kenya	0.035	GHE (2014)
<u>Lung cancer</u>			

Prevalence	Kenya	0.00003	GHE (2014)
IHD			
Prevalence	Kenya	0.006	GHE (2014)
Stroke			
Prevalence	Kenya	0.007	GHE (2014)

Table D19. Mortality rate due to disease (MRk, in deaths/10000 people-yr)

Description	Location	Value	Source
Acute lower respiratory illness			
Mortality rate	Kenya	0.0027	WHO (2014)
COPD			
Mortality rate	Kenya	0.00004	WHO (2014)
Lung cancer			
Mortality rate	Kenya	0.00001	WHO (2014)
IHD			
Mortality rate	Kenya	0.0002	WHO (2014)
Stroke			
Mortality rate	Kenya	0.0005	WHO (2014)

Notes: Statistics from the WHO are from the country-level Global Burden of Disease Estimates: http://www.who.int/healthinfo/mortality_data/en/.

Table D20. Exposure adjustment parameter (ε_i)

Description	Location	Median value	Source
Traditional			
Derived	From exposure study ratios	0.51	Author calculations
ICS			
Derived	From exposure study ratios	0.71	Author calculations

Table D21. Biomass harvesting that is non-renewable (ψ, in %)

Description	Location	Value
	Kenya	61.1

Notes: Data from Bailis et al. (2015)

Table D22. Household size (hhsize)

Description	Location	Value	Source
Nairobi household size	Kenya	2.98	Kenya National Bureau of Statistics (2018)
Average # < 5 yrs old	Kenya	0.79	DHS

Table D23. % of households using solid fuels (sfu)

Description	Location	Value	Source
	Kenya (Nairobi)	5.51%	Kenya National Cooking Sector Study (2019)

Table D24. Private discount rate

Country	Value	Source
Ethiopia	0.39	Poulos & Whittington (2000)
Ethiopia	1.1	Holden et al (1998)
Zambia	0.53	Holden et al (1998)
Statistics – Mean (SD)	**0.67 (0.38)**	

Table D25. Particulate emissions for stove fuel combinations ($\varepsilon_{PM2.5,i,m}$, in 24-hr µg/m^3 PM$_{2.5}$)

Description	Location	Value	Source
Traditional charcoal - Jiko	Laboratory	255 (532)	Imputed from Jetter et al (2009)
Charcoal ICS	Laboratory	182.1 (144.1)	Jeuland et al (2018)
Kerosene	Various	55.25	Jeuland et al (2018)
LPG	Various	43.22	Pope et al (2020)
Ethanol – No data[1]			

[1] Assuming PM$_{2.5}$ emissions for ethanol stoves are the same as that for LPG stoves.

Table D26. Other emissions factors for traditional charcoal stoves ($\varepsilon_{j,ICS,charcoal}$)

Description	Value	Source
CO2 (g/MJ fuel)		
Jiko Kenya	531	Jetter et al (2012)
CO (g/MJ fuel)		
Jiko Kenya	44.4	Jetter et al (2012)
CH4 (g/MJ fuel)		
Jiko Kenya	3.80	Jetter et al (2012)

N2O (g/MJ fuel)	0.0039	Zhang et al (2000)
BC (g/MJ fuel) - imputed	0.162	
OC (g/MJ fuel) - imputed	0.446	

Table D27. Other emissions factors for improved charcoal stoves ($\varepsilon_{j,ICS,charcoal}$)

Description	**Value**	**Source**
CO2 (g/MJ fuel)		
Coal briq metal flue	643	Zhang et al (2000)
Honeycomb coal metal flue	742	Zhang et al (2000)
Honeycomb coal ICS no flue	303	Zhang et al (2000)
Statistics – Mean (SD)	**562.7 (230.3)**	
CO (g/MJ fuel)		
Coal briq metal flue	18.1	Zhang et al (2000)
Honeycomb coal metal flue	25.6	Zhang et al (2000)
Honeycomb coal ICS no flue	6.52	Zhang et al (2000)
Statistics – Mean (SD)	**16.7 (9.6)**	
CH4 (g/MJ fuel)		
Coal briq metal flue	2.65	Zhang et al (2000)
Honeycomb coal metal flue	1.08	Zhang et al (2000)
Honeycomb coal ICS no flue	0	Zhang et al (2000)
Statistics – Mean (SD)	**1.24 (1.33)**	
N2O (g/MJ fuel)		
Coal briq metal flue	0.0389	Zhang et al (2000)
Honeycomb coal metal flue	0.119	Zhang et al (2000)
Honeycomb coal ICS no flue	0.0489	Zhang et al (2000)
Statistics – Mean (SD)	**0.069 (0.044)**	
BC (g/MJ fuel)		
Charcoal Jiko	0.022	MacCarthy et al (2008)
Bituminous coal	0.0052	Zhi et al (2008)
Statistics – Mean (SD)	**0.014 (0.012)**	
OC (g/MJ fuel)		
Charcoal Jiko	0.35	Zhi et al (2008)
Hard coal in brick kiln	0.44	Bond et al (2004)
Statistics – Mean (SD)	**0.396 (0.069)**	

Table D28. Other emissions factors for kerosene stoves ($\varepsilon_{j,ICS,kerosene}$)

Description	**Value**	**Source**
CO2 (g/MJ fuel)		
Kerosene-wick	140.4	Smith et al (2000)
Kerosene-press	145.2	Smith et al (2000)
Kerosene-wick	158	Zhang et al (2000)
Kerosene-press	162	Zhang et al (2000)
Statistics – Mean (SD)	**151.4 (10.3)**	

CO (g/MJ fuel)		
Kerosene-wick	0.8186	Smith et al (2000)
Kerosene-press	3.064	Smith et al (2000)
Kerosene-wick	0.378	Zhang et al (2000)
Kerosene-press	0.446	Zhang et al (2000)
Statistics – Mean (SD)	**1.2 (1.3)**	
CH4 (g/MJ fuel)		
Kerosene-wick	0.0134	Smith et al (2000)
Kerosene-press	0.0528	Smith et al (2000)
Kerosene-press	0.00052	Zhang et al (2000)
Kerosene-wick	0.0022	Zhang et al (2000)
Statistics – Mean (SD)	**0.017 (0.024)**	
N2O (g/MJ fuel)		
Kerosene-wick	0.0777	Smith et al (2000)
Kerosene-press	0.0324	Smith et al (2000)
Statistics – Mean (SD)	**0.055 (0.032)**	
BC (g/MJ fuel)		
Kerosene	0.016	MacCarthy et al (2008)
Kerosene	0.007	Bond et al (2004)
Statistics – Mean (SD)	**0.012 (0.006)**	
OC (g/MJ fuel)		
Kerosene	0.0057	Zhang et al (2000) + Bond et al. (2004)

Table D29. Other emissions factors for LPG stoves ($\varepsilon_{j,ICS,gas}$)

Description	**Value**	**Source**
CO2 (g/MJ fuel)		
LPG	125.6	Smith et al (2000)
LPG-trad	140	Zhang et al (2000)
LPG-IR	153	Zhang et al (2000)
Statistics – Mean (SD)	**139.5 (13.7)**	
CO (g/MJ fuel)		
LPG	0.6076	Smith et al (2000)
LPG-trad	0.0996	Zhang et al (2000)
LPG-IR	1.03	Zhang et al (2000)
Statistics – Mean (SD)	**0.579 (0.466)**	
CH4 (g/MJ fuel)		
LPG	0.00203	Smith et al (2000)
LPG-trad	0.0231	Zhang et al (2000)
LPG-IR	0.0158	Zhang et al (2000)
Statistics – Mean (SD)	**0.014 (0.012)**	
N2O (g/MJ fuel)		
LPG	0.27	Smith et al (2000)
LPG-trad	0.15	Zhang et al (2000)
LPG-IR	0.00	Zhang et al (2000)

Statistics – Mean (SD)	**0.142 (0.135)**	
BC (g/MJ fuel)		
LPG	0.0037	MacCarthy et al (2008)
LPG	0.0025	Bond et al (2004)
Statistics – Mean (SD)	**0.003 (0.004)**	
OC (g/MJ fuel)		
LPG	0.00193	Bond et al (2004) & Zhang et al. (2000)

Appendix E. Parameterization of the model: Summary of data sources– Nepal Analysis

Table E1. Stove costs (c_i^c, in $)

Description	Location	Value	Source
Traditional firewood	Nepal	0.0	Stakeholder interviews (2019)
Natural draft ICS	South Asia	22.3	Jeuland et al. (2018)
Liquefied petroleum gas	Nepal (Kathmandu Valley)	20.1	Duke Kathmandu Valley Survey (2019)
Electric			
Ascent 50-60 Hz Induction cooker	Nepal	67.3	Daraz Website[1]
Induction cooktop (Black, touch panel)	Nepal	90.4	Daraz Website
Infra ray induction 2000 W	Nepal	22.6	Daraz Website
Baltra BIC-106 Impression 2000 W Induction Cooker	Nepal	34.4	Daraz Website
Baltra BIC-106 Impression 2000 W Electric Induction Cooker	Nepal	34.8	Daraz Website
Baltra BIC-106 Impression 2000 W Electric Induction Cooker	Nepal	37.1	Daraz Website
Baltra BIC-106 Impression 2000 W Electric Induction Cooker	Nepal	38.4	Daraz Website
Other brands	Nepal	40.1-60.3	Daraz Website
Statistics – Mean (sd)		**46.9 (22.0)**	

Notes: For computation of statistics, we use the median value for stoves with ranges of costs.

[1] Costs of electric stove cooktops in Nepal were taken from this website: https://www.daraz.com.np/cooktops/?page=3&sort=priceasc

Table E2. Program costs (c^p, in $/hh-yr)

Description	Location	Value	Source
Expert estimates Transitional and clean stoves	Global	17.0	WHO BAR-HAP Tool (2020)

Table E3. Maintenance cost (c_i^m, in \$/yr)[1]

Description	Location	Value	Source
Natural draft ICS	South Asia	4.71	Jeuland et al. (2018)
LPG			
NG 4B SS	Mexico	4.29	Clean Cooking Catalog
NG 4B	Mexico	4.00	Clean Cooking Catalog
NG 2B	Mexico	2.00	Clean Cooking Catalog
NG 2B gas	Mexico	2.10	Clean Cooking Catalog
NG 2B SS	Mexico	2.00	Clean Cooking Catalog
LPG	Nepal	1.47	Pokharel (2004)
Statistics – Mean (sd)		**2.6 (1.2)**	
Electric – no data[2]			

[1] Assuming 50% depreciation, [2] Assuming maintenance cost of electric stove is the same as that of LPG stove.

Table E4. Lifespan of stove (T_i, in years)

Description	Location	Value	Source
Natural draft ICS	South Asia	3.55	Jeuland et al. (2018)
LPG	Nepal (Kathmandu Valley)	5.68	Duke Kathmandu Valley Survey (2019)
Electric – no data[1]			

[1] Assuming lifespan of electric stove is the same as that of LPG stove.

Table E5. Usage rate (χ in %)

Description	Location	Value	Source
Firewood	Kathmandu, Nepal	7.6	Nepal Census (2011)
Firewood	Lalitpur, Nepal	17.9	Nepal Census (2011)
Firewood	Bhaktapur, Nepal	25.2	Nepal Census (2011)
Firewood	Nepal (Urban)	48.4	DHS (2016)
Statistics – Mean (sd)		**29.9 (26.2)**	
Firewood	Nepal (Kathmandu Valley)	11.4	Duke Kathmandu Valley Survey (2019)
LPG	Kathmandu, Nepal	88.3	Nepal Census (2011)
LPG	Lalitpur, Nepal	77.2	Nepal Census (2011)
LPG	Bhaktapur, Nepal	69.2	Nepal Census (2011)
LPG	Nepal (Urban)	46.4	DHS (2016)
Statistics – Mean (sd)		**65.3 (26.8)**	
LPG	Nepal (Kathmandu Valley)	84.3	Duke Kathmandu Valley Survey (2019)
Electricity	Kathmandu, Nepal	0.05	Nepal Census (2011)
Electricity	Lalitpur, Nepal	0.24	Nepal Census (2011)
Electricity	Bhaktapur, Nepal	0.18	Nepal Census (2011)
Statistics – Mean (sd)		**0.1 (0.78)**	
Electricity	Nepal (Urban)	1.2	DHS (2016)

Table E6. Average daily cooking time with stove ($cook_0$, in hr/day)

Description	Location	Value	Source
Traditional firewood stove	Nepal (Kathmandu Valley)	2.4	Duke Kathmandu Valley Survey (2019)
LPG	Nepal (Kathmandu Valley)	1.57	Duke Kathmandu Valley Survey (2019)
Electric – no data[1]			

[1] Assuming cooking time for electric stoves is the same as that for LPG stoves.

Table E7. Time efficiency of ICS relative to traditional stove (te_i, as a ratio)[1]

Description	Item	Value	Source
LPG			
		0.60	MacCarthy et al (2010)
		0.83	MacCarthy et al (2010)
Generic LPG	Rice	0.89	Houngan et al (2013)
Generic LPG	Beans	0.96	Houngan et al (2013)
Generic LPG	Dry corn	1.12	Houngan et al (2013)
Oryx LPG	Rice	0.77	Houngan et al (2013)
Oryx LPG	Beans	0.60	Houngan et al (2013)
Oryx LPG	Dry corn	0.93	Houngan et al (2013)
		0.53	Anozeia (2007)
Statistics – Mean (sd)		**0.8 (0.2)**	
Electric			
Generic Electric	Rice	0.95	Houngan et al (2013)
Generic Electric	Beans	0.96	Houngan et al (2013)
Generic Electric	Dry corn	1.06	Houngan et al (2013)
		0.60	Anozeia (2007)
Statistics – Mean (sd)		**0.89 (0.20)**	

[1,2] Assuming time efficiency for LPG and Electric stoves relative to each other is 1.

Table E8. Thermal efficiency of stove (ϵf_i, in %)

Description	Details	Value	Source
Traditional biomass stove			
Generic traditional stove		7%	Wiskerke et al (2010)
Three stone stove	Water boiling test	21.4%	Zhang et al (2000)
Three stone stove	Water boiling test	17.6%	Smith et al (2000)
Three stone stove	Water boiling test	18.1%	Smith et al (2000)
Three stone stove	Water boiling test	18.2%	Smith et al (2000)
Statistics – Mean (sd)		**16.5 (5.5)**	
LPG			
LPG	Thermal efficiency	42	Zhang et al (2000)
Anard	Thermal efficiency	64	Clean Cooking Catalog
Statistics – Mean (sd)		**53.0 (15.6)**	
Electric			
Ascent 50-60 Hz Induction cooker	Kilo-watt	1.80	Daraz website
Induction - Sayona	Kilo-watt	2.00	Daraz website
Induction Cooker Sy20V98	Kilo-watt	1.80	Daraz website
Induction - Glass Top	Kilo-watt	2.20	Daraz website
Induction - Ailipu Company	Kilo-watt	2.00	Daraz website
Baltra Clark Induction Cooktop (Black)	Kilo-watt	2.00	Daraz website
Baltra Cosmo + Pro Induction Cooktop (Black)	Kilo-watt	2.00	Daraz website

Baltra Feel (Infrared) Induction Cooktop (Black	Kilo-watt	2.00	Daraz website
Diamond Seiko Induction Cooktop	Kilo-watt	2.00	Daraz website
Diamond Rado Induction Cooktop Touch Control	Kilo-watt	2.00	Daraz website
Statistics – Mean (sd)	**kW-hr/hr cooking**	**1.98**	

Table E9. Calorific value (or fuel energy density) for stove (μ_i)

Description	Details	Value	Source
Wood		16	IOR Energy[1]
LPG		48.3	IOR Energy[1]

[1] http://w.astro.berkeley.edu/~wright/fuel_energy.html

Table E10. Amount of fuel used for cooking ($fuelckg_0$, in kg/day)

Description	Location	Value	Source
Traditional	Nepal	2.8	Johnson et al (2013)
Traditional	Nepal	11.2	Johnson et al (2013)
Statistics – Mean (sd)		**0.47 (0.40)**	
ICS	Nepal	2.5	Johnson et al (2013)
ICS	Nepal	7.5	Johnson et al (2013)
Statistics – Mean (sd)[1]		**0.33 (0.24)**	

[1] Assuming amount of fuel used for LPG and Electric stoves is the same as that for ICS.

Table E11. Percentage of people buying wood (f)

Description	Location	Value	Source
Firewood	Nepal (Kathmandu Valley)	5.6	Duke Kathmandu Valley Survey (2019)

Table E12. Average daily wood fuel collection time ($collt_0$, in hr/day)

Description	Location	Value	Source
Survey measure	Nepal	1.03	Nepal et al (2011)
Author-calculated	Nepal	0.36	Amacher (1996)
Author-calculated	Nepal	0.37	Amacher (1996)
Survey measure	Nepal	2.50	Kumar & Hotchkiss (1988)
Statistics – Mean (sd)		**1.1 (1.0)**	

Table E13. Shadow value of time (fraction of wage) (κ^t)

Description	Location	Value	Source
Time spent obtaining cholera vaccines	Mozambique	0.35	Jeuland et al. (2010)
Value of time spent traveling – recent estimate	UK	0.33	Accent/Hague (1999), as cited in Mackie et al. (2002)
Value of time spent traveling – high estimate	UK	0.43	MVA, ITS, TSU (1987), as cited in Mackie et al. (2002)
Transport choices	UK	0.22	Quarmby (1967)
Transport choices	UK	0.45	Lisco (1968)
Choice of driving route	US	0.40	Thomas (1968)
Urban commuting choices	UK	0.22	Stopher (1969)
Choice of public transport alternatives	UK	0.3	Lee & Dalvie (1969)
Time spent collecting water	Kenya	1.2	Whittington et al. (1990)
Statistics – Mean (sd)		**0.43 (0.30)**	

Table E14. Minimum wage rates (W, in US\$2015 per hr)

Country	Value
Nepal	0.47

Notes: Values obtained from https://en.wikipedia.org/wiki/List_of_minimum_wages_by_country.

Table E15. Average daily fuel preparation time for LPG and Electric stoves (*prep*, in hr/day)

By assumption 0 hours (no data).

Table E16. Cost of fuel (p_i in \$)

Descrption	**Location**	**Value**	**Source**
Firewood ($/kg)	Nepal (Kathmandu Valley)	0.23	Duke Kathmandu Valley Survey (2019)
LPG ($/kg)			
	Nepal	1.02	Nepal Oil Corporation (Sep 29, 2014)
	Nepal	0.99	Nepal Oil Corporation (Aug 2, 2015)
	Nepal	0.97	Nepal Oil Corporation (Sep 1, 2015)
	Nepal	0.95	Nepal Oil Corporation (Aug 2, 2016)
	Nepal	0.92	Nepal Oil Corporation (Sep 2, 2016)
	Nepal	0.93	Nepal Oil Corporation (Feb 1, 2017)
	Nepal	0.92	Nepal Oil Corporation (Jul 2, 2017)
	Nepal	0.93	Nepal Oil Corporation (Nov 1, 2017)
	Nepal	0.92	Nepal Oil Corporation (Nov 2, 2017)
	Nepal	0.93	Nepal Oil Corporation (Dec 8, 2017)
	Nepal	0.97	Nepal Oil Corporation (Dec 3, 2018)
	Nepal	0.97	Nepal Oil Corporation (Apr 24, 2019)
	Nepal	0.97	Nepal Oil Corporation (Jun 6, 2019)
Statistics – Mean (sd)		**0.95 (0.03)**	
	Nepal (Kathmandu Valley)	0.91	Duke Kathmandu Valley Survey (2019)
Electric			
	Bangladesh	0.061	See notes
	Bhutan	0.031	See notes
	India	0.070	See notes
	Pakistan	0.085	See notes
	India	0.108	Pokharel (2004)
	Nepal	0.112	Stakeholder interviews (2019)
Statistics – Mean (sd)		**0.08 (0.03)**	

Notes: For electricity prices, unless otherwise noted, source is https://en.wikipedia.org/wiki/Electricity_pricing. All values are in 2015$US.

Table E17. Learning hours (*l*, in hours)

By assumption (no data)

Table E18. Incidence/prevalence of disease (*IR_k*, in cases per 100 persons-yr)

Description	Location	Value	Source
Acute lower respiratory illness			
Incidence	Nepal	0.015	GBD (2017)
COPD			
Prevalence	Nepal	0.041	GBD (2017)
Lung cancer			
Prevalence	Nepal	0.000082	GBD (2017)
IHD			
Prevalence	Nepal	0.0126	GBD (2017)
Stroke			
Prevalence	Nepal	0.00668	GBD (2017)

Table E19. Mortality rate due to disease (*MR_k*, in deaths/10000 people-yr)

Description	Location	Value	Source
Acute lower respiratory illness	Nepal	0.002669	GBD (2017)
COPD	Nepal	0.000613	GBD (2017)
Lung cancer	Nepal	0.000079	GBD (2017)
IHD	Nepal	0.001025	GBD (2017)
Stroke	Nepal	0.000471	GBD (2017)

Notes: Statistics for 2017 are from the Institute for Health Metrics and Evaluation Estimates: http://ghdx.healthdata.org/gbd-results-tool

Table E20. Exposure adjustment parameter (ε_i)

Description	Location	Median value	Source
Traditional			
Derived	From exposure study ratios	0.51	WHO BAR-HAP Tool
ICS			
Derived	From exposure study ratios	0.71	WHO BAR-HAP Tool

Table E21. Biomass harvesting that is non-renewable (ψ, in %)

Description	Location	Value
	Nepal	52.8

Notes: Data from Bailis et al. (2015)

Table E22. Household size (*hhsize*)

Description	Location	Value	Source
Household size	Kathmandu, Nepal	4.00	Nepal Census (2011)
Household size	Lalitpur, Nepal	4.26	Nepal Census (2011)
Household size	Bhaktapur, Nepal	4.44	Nepal Census (2011)
Statistics – Mean (sd)		**4.23 (0.22)**	
Number of < 5 yrs old	Kathmandu, Nepal	0.26	Nepal Census (2011)
Number of < 5 yrs old	Lalitpur, Nepal	0.27	Nepal Census (2011)
Number of < 5 yrs old	Bhaktapur, Nepal	0.27	Nepal Census (2011)
Statistics – Mean (sd)		**0.26 (0.02)**	

Table E23. % of households using solid fuels (*sfu*)

Description	Location	Value	Source
	Nepal (Kathmandu Valley)	11.4	Duke Kathmandu Valley Survey (2019)

Table E24. Private discount rate

Country	Value	Source
Ethiopia	0.39	Poulos & Whittington (2000)
Bulgaria	0.38	Poulos & Whittington (2000)
Indonesia	0.45	Poulos & Whittington (2000)
Sri Lanka	0.23	Gunatilake & Wickramasinghe (2007)
Malaysia	2.77	Teh et al (2014)
Fiji	2.08	Teh et al (2014)
Indonesia	0.93	Holden et al (1998)
Ethiopia	1.1	Holden et al (1998)
Zambia	0.53	Holden et al (1998)
Vietnam	0.335	Anderson et al (2004)
Vietnam	0.007	Anderson et al (2004)
Timor-Leste	0.127	Botelho et al (2006)
Statistics – Mean (sd)	**0.78 (0.84)**	

Table E25. Particulate emissions for stove fuel combinations ($\varepsilon_{PM2.5,i,m}$, in 24-hr µg/m^3 PM$_{2.5}$)

Description	Location	Value	Source
Traditional biomass			
Kitchen levels			
Statistics – Mean (sd)	Various	833.495 (801.158)	Pope et al. (Ongoing meta-analysis)
LPG			
Kitchen levels			
Statistics – Mean (sd)	Various	43.22 (37.30)	Pope et al. (Ongoing meta-analysis)
Electric			
Kitchen levels			
Statistics – Mean (sd)	Various	40.60 (31.54)	Pope et al. (Ongoing meta-analysis)

Table E26. Other emissions factors for traditional biomass stoves ($\varepsilon_{j,trad,biomass}$)

Description	Value	Source
CO2 (g/MJ fuel)		
Accacia-trad mud	506.3	Smith et al (2000)
Acacia 3R	502.8	Smith et al (2000)
Euc 3R	566.1	Smith et al (2000)
Wood-metal no flue	545.0	Zhang et al (2000)
Brush-metal no flue	458.0	Zhang et al (2000)
Statistics – Mean (sd)	**515.6 (41.8)**	
CO (g/MJ fuel)		
Accacia-trad mud	24.2	Smith et al (2000)
Acacia 3R	23.7	Smith et al (2000)
Euc 3R	22.2	Smith et al (2000)
Wood-metal no flue	14.6	Zhang et al (2000)
Brush-metal no flue	36.6	Zhang et al (2000)
Statistics – Mean (sd)	**24.2 (7.9)**	
CH4 (g/MJ fuel)		
Accacia-trad mud	1.43	Smith et al (2000)
Acacia 3R	3.44	Smith et al (2000)
Euc 3R	1.04	Smith et al (2000)
Wood-metal no flue	0.66	Zhang et al (2000)
Brush-metal no flue	1.95	Zhang et al (2000)
Statistics – Mean (sd)	**1.71 (1.08)**	
N2O (g/MJ fuel)		
Accacia-trad mud	0.034	Smith et al (2000)
Acacia 3R	0.065	Smith et al (2000)
Euc 3R	0.027	Smith et al (2000)
Wood-metal no flue	0.266	Zhang et al (2000)
Brush-metal no flue	0.606	Zhang et al (2000)

Statistics – Mean (sd)	**0.20 (0.25)**	
BC (g/MJ fuel)		
3R	0.306	MacCarthy et al (2008)
3R	0.278	Bond et al (2013)
Statistics – Mean (sd)	**0.29 (0.02)**	
OC (g/MJ fuel)		
3R	0.25	Roden et al (2009)
Traditional	1.09	Roden et al (2009)
Traditional	1.07	Roden et al (2009)
Statistics – Mean (sd)	**0.80 (0.48)**	

Table E27. Other emissions factors for LPG stoves ($\varepsilon_{j,ICS,gas}$)

Description	**Value**	**Source**
CO2 (g/MJ fuel)		
LPG	125.6	Smith et al (2000)
LPG-trad	140	Zhang et al (2000)
LPG-IR	153	Zhang et al (2000)
Statistics – Mean (sd)	**139.5 (13.7)**	
CO (g/MJ fuel)		
LPG	0.6076	Smith et al (2000)
LPG-trad	0.0996	Zhang et al (2000)
LPG-IR	1.03	Zhang et al (2000)
Statistics – Mean (sd)	**0.58 (0.47)**	
CH4 (g/MJ fuel)		
LPG	0.00203	Smith et al (2000)
LPG-trad	0.0231	Zhang et al (2000)
LPG-IR	0.0158	Zhang et al (2000)
Statistics – Mean (sd)	**0.01 (0.01)**	
N2O (g/MJ fuel)		
LPG	0.27	Smith et al (2000)
LPG-trad	0.15	Zhang et al (2000)
LPG-IR	0.00	Zhang et al (2000)
Statistics – Mean (sd)	**0.14 (0.13)**	
BC (g/MJ fuel)		
LPG	0.0037	MacCarthy et al (2008)
LPG	0.0025	Bond et al (2004)
Statistics – Mean (sd)	**0.003 (0.004)**	
OC (g/MJ fuel)		
LPG	0.00193	Bond et al (2004) & Zhang et al. (2000)

Table E28. Other emissions factors for electric stoves ($\varepsilon_{j,ICS,electric}$)

Since electricity is generated using hydro resources (i.e. renewable sources), we assume there are no emissions from electricity generation.