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Substituting LP Gas for Wood: Carbon and Deforestation Impacts

A report of the World LP Gas Association

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Sparing carbon and trees – one stove at a time

Cooking with LP Gas, rather than wood, combats global warming and deforestation.

In developed and developing countries, biofuels could hardly be viewed more differently. In developed countries they are modern, even trendy, with broad government support driving consumption levels to record highs. In the developing world, typified by the traditional three-stone fire, biofuels are a symbol of the not-so-good-old days. Known mainly by their common names of wood and charcoal, they are seen as a barrier to economic progress and a major source of illness.

Governments have recognised this, prompting a revolution in energy use that is already underway. Part of this involves a massive shift from cooking with wood and other forms of biomass to cooking with liquefied petroleum gas (LP Gas). According to the International Energy Agency's vision of the future, the so-called 'Universal Modern Energy Access Case' (UMEAC), nearly half a billion people will make the switch by 2015, with another three-quarter billion joining them by 2030.

For users, the reasons are obvious. LP Gas is far more energy concentrated: annual per capita cooking requires 36 kg, as opposed to 400 kg of wood. It cooks more efficiently, transferring 60% of its energy content to the pot, compared to wood's 10-20%. Unlike wood, an LP Gas fire can easily be turned on and off. Instead of emitting choking smoke, its exhaust is problem-free for indoor use. All these advantages lead to improved wealth and health.

Somewhat less obvious, but still important are the benefits to the natural environment. Switching from wood to LP Gas can significantly reduce emissions of the number one greenhouse gas, carbon dioxide, and it can seriously mitigate the scourge of deforestation. That's right, increased substitution of a fossil fuel for a biofuel can yield serious benefits for nature.

Re-thinking biofuels

This might have seemed unimaginable some ten years ago, when biofuels were viewed by many as a cure-all for our warming climate. By the end of the last decade, both Europe and America, prompted mainly by the desire to cut carbon, announced bold targets for biofuels with their Renewable Energy Directive and Renewable Fuels Standard.

Even before the ink on these acts was dry, however, the pendulum of informed opinion had begun to swing back from euphoria to caution. Critical voices that have been sounding since mid-decade began to find traction in policy advice issued by the IEA (Task Force 38 on Greenhouse Gas Balances of Biomass and Bioenergy Systems), the US EPA (Accounting Framework for Biogenic CO_2 Emissions from Stationary Sources), the European Environmental Agency (Greenhouse Gas Accounting in Relation to Bioenergy) and ISO (13065: Sustainability Criteria for Bioenergy)[1]. They called not for a wholesale rejection of biofuels, but for a more nuanced view – i.e. sometimes they are good, sometimes they are bad.

In the case of traditional cooking, wood comes out poorly against LP Gas, both on carbon emissions and deforestation. The analyses behind these conclusions have similarities, but they are not identical. Let's look at them individually.

Carbon savings - calculated

The classic carbon-related argument for using wood as a fuel can still be heard regularly: "The tree will grow back." Unfortunately, in the time-constrained battle against global warming, this is not enough, because the tree grows back too slowly. Even in the fastest-tree-growing areas of the tropics, it takes forests more than 60 years to regenerate after a harvest. Regrowth takes at least a decade longer in temperate zones, and can last for one-to-two centuries in boreal regions of the north. In any of these cases, this is nowhere near soon enough to meet the 80% emissions-reduction targeted by the G8 nations for 37 years from now, in 2050.

Besides, simply growing back the tree does not create carbon neutrality. Even in a tropical zone, it will take more than a century, post-combustion, for LP Gas and wood to come to parity in their carbon emissions. By most policy measures, that will be too late.

[1] The author sits in the IEA and ISO groups, and his research has been recognized in the EEA and EPA opinions.

One of the main reasons for this is that burning wood is dramatically less carbon-efficient than burning LP Gas – and the primary cause for this is chemistry. Typical air-dried wood consists of only about 50% fuel. The rest is molecularly-bound oxygen (in carbohydrates and lignin) plus left-over moisture (a fresh-cut tree contains some 50% water by weight). Neither of these burns, and vaporising the moisture steals valuable combustion energy. LP Gas, by contrast, is all fuel. There also is an inherent difference in carbon content. Dry wood has a majority of carbon atoms to those of hydrogen, while in propane and butane – LP Gas's main constituents – carbon atoms are in the minority.

Already in pre-combustion the carbon gap is wide: there, wood is nearly twice as carbon intensive (per unit of energy) as LP Gas. Combine that with its lower combustion efficiency, and the die is cast. Per unit of delivered cooking heat, burning wood generates about seven times the carbon of LP Gas.

So, switching from wood to LP Gas can reduce cooking's carbon emissions significantly. Over 63.5 years (the average regeneration period for a harvested forest in the tropics, where most traditional cooking happens) switching cuts net-CO_2 output to the atmosphere by two-thirds. Yes, the tree finally does grow back, and this analysis fully accounts for that. Still, LP Gas is the cleaner option.

All these changes, stove-by-stove, can add together to a globally significant impact. If, as the UMEAC scenario projects, 1.175×10^9 people switch from wood to LP Gas, this would create to a net annual atmospheric reduction (over 63.5 years) of 279 million t of carbon dioxide. That is roughly equal to current annual emissions from mid-sized countries such as Taiwan or Thailand. At a more human scale, the annual savings per person are 237 kg CO_2, or 1,186 kg for an average developing-world household of five people. This latter figure is equal to the emissions of an average, new European car being driven for 7,900 km.

Speaking for the trees

Sadly, in much of the developing world, the tree does not even grow back, slowly or otherwise. As the UN's Food and Agricultural Organisation points out in its latest 'Global Forest Resources Assessment' of 2010, deforestation is continuing its centuries-long march.

Globally it slowed slightly over the last decade compared to the 1990s, but this is in large part due to afforestation in the developed world as well as in parts of India and China.

Of course this is welcome, but it comes off a severely depleted base. Meanwhile, across most of the developing regions of Africa, Asia and Latin America, unsustainable harvesting drove carbon stock in forests down to record lows.

At the whole-earth level, says the FAO, half of the wood harvested was for fuel. The question is: how much of this wood was intentionally harvested as such, and how much was a 'residue' or waste of harvesting for other reasons (lumber, plantation, pasture, cropping or industrial/commercial/residential use). This clearly deserves further investigation, yet a survey of the science suggests a rough 50/50 split. Particularly in urban areas, wood supplies are being sourced as on-purpose products, not unavoidable residues or wastes.

The UMEAC swap from wood to LP Gas could make a serious dent in this forest rundown, and for much the same reasons as it would reduce net carbon emissions. The shift by 2015 of 445 million people from wood to LP Gas would spare 440,000 hectares/year of forest a year. By 2030, with over a billion people switched to LP Gas, 1.2 million hectares/year would be saved – equivalent to nearly one-quarter of current global deforestation.

At a more personal scale, switching 100 households from consuming 200 tonnes of harvested wood a year to consume instead 1.8 tonnes of LP Gas would save one hectare of forest each year. Each household would save about 100 square metres of forest. A typical 13-kg cylinder of LP Gas would avert deforestation of a 7 m² forest area.

It will take a village, actually a lot of villages, not to mention a number of major cities. But this could make a serious dent in carbon emissions and save forests, which of course are the planet's lungs, home to much biodiversity, and – especially in developing countries – a key source of employment. Switching from wood to LP Gas is an idea whose time has come.

Some

540 million

households around the world, about 2.7×10^9 people, currently use biomass to fuel their cooking.

1.0 Reducing carbon emissions by substituting LP Gas for wood

Some 540 million households around the world, about 2.7×10^9 people, currently use biomass to fuel their cooking. While their numbers are still growing, major changes in cooking technology are underway. According to the 'Universal Modern Energy Access Case' (UMEAC) projected by International Energy Agency (IEA), there will be a large shift from biomass to liquefied petroleum gas (LP Gas). By 2015, the IEA projects, 445 million people will convert some of their biomass consumption for cooking to LP Gas, and by 2030 another 730 million people will follow suit. This paper investigates the impact of that UMEAC shift on carbon emissions. It finds that switching from wood to LP Gas can reduce cooking's carbon emissions by two-thirds.

1.1 Introduction: cleaner cooking and global warming

Bringing cleaner cooking to the developing world has in the past decade gained ever increasing attention from the developed world. Organisations such as the Global Alliance for Clean Cookstoves[2] and the National Biomass Cookstoves Initiative[3] (Venkataraman et al., 2010) have been created to combat the negatives of cooking with traditional cookstoves and open fires. The International Energy Agency (IEA) has proposed a 'Universal Modern Energy Access Case' (IEA, 2010) (IEA, 2012), referred to as UMEAC, that would extend clean cooking (and electrification) to the entire world by 2030.

Traditional-style cooking has three primary negatives. One is economic disadvantage to its practitioners. Traditional-cooking households spend significant (and increasing) amounts of their time collecting fuel, time that could be more productively spent in other types of work. Another is injury and disease. Carrying wood exposes carriers to potential assault by humans or animals, plus bodily damage from the strain. Ailments such as asthma, bronchitis, child pneumonia, lung cancer, chronic obstructive pulmonary disease, heart disease, as well as low birth-weight in children can be caused by chronic exposure to the exhausts of traditional cookers. Then there are environmental damages: excess emissions of global warmers carbon-dioxide and black carbon; and deforestation.

To avoid these negatives, one option is to switch from wood to another fuel, for instance liquefied petroleum gas, commonly known as LP Gas (Thompson et al., 2011). Clearly, this option meets the criteria of large increases in combustion efficiency, fuel efficiency, or both, proposed by (Ruiz-Mercado et al., 2011, p 7557). So, how does switching perform with respect to global warming?

To date, the global warming impact has not been quantified. In its most recent discussion of UMEAC (IEA et al., 2010, p 22), the IEA comments that "the impact on greenhouse-gas emissions of switching to advanced biomass technologies or LP Gas is very difficult to quantify, because of the diversity of factors involved, including the particular fuels, the types of stoves and whether the biomass is replaced by new planting and that a sustainable forestry management programme is in place. But it is widely accepted that improved stoves and greater conversion efficiency would result in emissions reductions."

The paper focuses on this 'very difficult', yet very important quantification. It compares the net emissions, i.e. carbon footprints, of cooking done with wood and with LP Gas.

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[2] http://www.cleancookstoves.org/
[3] http://www.mnre.gov.in/schemes/decentralized-systems/national-biomass-cookstoves-initiative/

1.2 Method

This analysis compares the carbon dioxide emissions of using wood to fuel traditional cooking to those of substituted LP Gas. The comparison is done using the general approach of life-cycle assessment or carbon footprinting (ISO, 2006a) (ISO, 2006b) (BSI et al., 2011). The functional unit is 1 GJ output of delivered cooking heat[4].

The comparison assumes that there are only two options – wood or LP Gas – and that one of them will be adopted. This is not shown explicitly in the main analysis, i.e. no baseline is shown. Near the end of the paper (section 1.5) this is presented with an explicit baseline as defined by (Johnson and Tschudi, 2012).

1.3 Definition of the systems

There are two main sub-systems in this type of cooking: the cooking system (of which there are two types, LP Gas and wood), and the forest system.

1.3.1 The cooking systems

For the base case comparison, four definitions (Table 1) are most important: carbon intensity, thermal efficiency, product/residue split and fuel required.

Table 1: Key components of the cooking systems, base case

Fuel	Carbon intensity kg CO_2/GJ (LHV)	Thermal efficiency Fuel LHV to cooking heat delivered	Product/residue split	Fuel required kg/GJ delivered heat
Wood	105.1 (Johnson and Tschudi, 2012)	15% (World Bank, 2006, p 39)	100% product, 0% residue	400 (World Bank, 2006, p 39)
LP Gas	7.4 well-to-stove (Johnson, 2012) plus 63.1 stove-to-stack (Atlantic Consulting, 2010) = Well-to-stack 70.5	60% (World Bank, 2006, p 39)	100% product, 0% residue	36 (World Bank, 2006, p 39)

Carbon intensities of both fuels are taken from previous work by the author, and are consistent with values found in general literature. The base case assumes that carbon in either fuel is converted fully to carbon dioxide. Thermal efficiencies are taken from a World Bank review, and are consistent with those found in the general literature, for example in (Smith et al., 2000). Both wood and LP Gas are assumed to be products, i.e. produced on purpose, as opposed to residues or wastes (European Commission, 2009).

An average developing-world family consists of five people (Bongaarts, 2001) that annually consume 5 GJ of useful energy in cooking (World Bank, 2006, p 39), i.e. 1 GJ per person per year. At 15% efficiency, 1 GJ delivered heat requires 400 kg of wood[5]; at 60% efficiency, 1 GJ requires 36 kg of LP Gas. For LP Gas, this is considerably higher than the 22 kg/person-year quoted by the IEA (IEA, 2006, p 15) (IEA, et al., 2010, p 22). However, this is not a disagreement, rather a case of different definitions. The 36-kg figure applies if the household cooks only with LP Gas. The 22-kg figure is an estimate of LP Gas usage in typical households, which often use multiple cooking fuels (World Bank, 2011b) (World Bank, 2011a). For instance, as (Ruiz-Mercado, et al., 2011) reports, families in Mexico's highlands typically use four different cookers: a three-stone fire, a Patsari stove, an LP Gas stove and a microwave oven. The first two burn biomass to prepare traditional foods such as tortillas and tamales; LP Gas is used for soups, meats and re-heating; the microwave is used for re-heating and making popcorn.

1.3.2 The forest 'system'

In the base case of this analysis, wood is harvested on-purpose as fuel; i.e. it is a product rather than a residue or waste (Table 1).

How quickly does the carbon emitted by the wood's combustion become re-sequestered by forest re-growth? For this we have drawn on the work of (WBGU, 1998) and (Müller-Wenk and Brandao, 2010), who have estimated 'relaxation times', i.e. the years needed for a harvested forest to return to its former state of forestation. These range from 62 to 238 years (Müller-Wenk and Brandao, 2010, Table 2, p 178), depending on the forest type and the extent of the harvesting.

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[4] GJ of delivered cooking heat is the approximate amount consumed in the developing world by one person in one year.
[5] At 15% moisture, a fairly typical value for air-dried wood.

1.4 Impact assessment

Carbon dioxide is the most accurately, most consistently measured global warmer emitted in fuel combustion. As (Johnson, 2012, Appendix A) points out, estimated emission factors for other species – methane, nitrous oxide and so forth – can vary considerably, and often they are not reported at all. Furthermore (and more importantly with respect to this analysis), only carbon dioxide is re-sequestered by the forest.

For both reasons, we have done the impact assessments for carbon dioxide only. A suitable piece of further research would be to do the assessment for all global warmers.

1.4.1 Wood vs LP Gas, in theory

Using the definitions above, the net carbon emissions of the two systems (wood and forest; LP Gas) have been plotted over time (Figure 1).

In both systems, 1 GJ of cooking heat is delivered, which calls for 400 kg of air-dried wood and 36 kg of LP Gas (a bit less than three typical 13-kg cylinders). The emissions, which are treated as a pulse in year zero, are derived from the factors above (Table 1).

Wood's emissions are

$$105.1 \div 15\% \times 100\% = 700.7 \text{ kg } CO_2/GJ$$

whereas LP Gas's emissions are

$$70.1 \div 60\% \times 100\% = 116.8 \text{ kg } CO_2/GJ$$

According to normal conventions of life-cycle accounting, the CO_2 emissions from LP Gas are not offset by re-sequestration, but the emissions from wood are[6]. The wood emissions are re-sequestered completely by the end of the 'relaxation' period. We have presented the re-sequestration as a linear progression[7]. For each system, the net carbon emission is simply the area above/under each curve (Figure 1), in units of CO_2 tonne-years. In keeping with conventions of environmental accounting, no discounting has been applied to future emissions.

Figure 1: Net carbon emissions for 1 GJ delivered heat, wood vs LP Gas
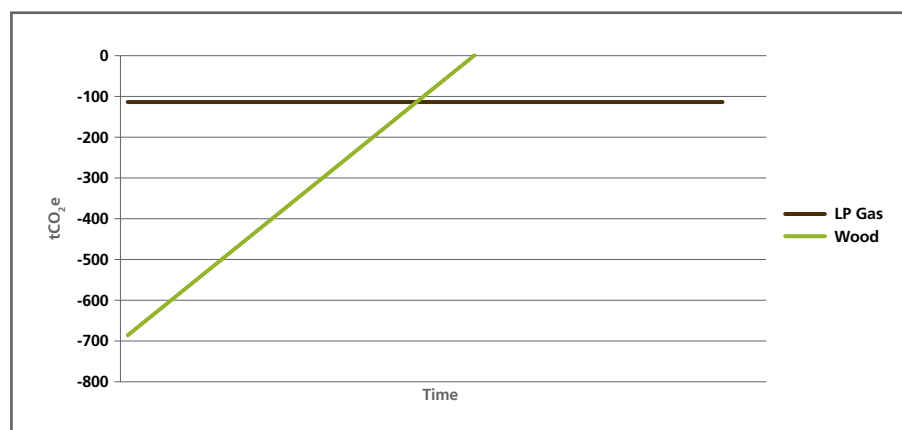
[6] The qualification starting this sentence is critical. In actual fact, of course the carbon dioxide from LP Gas is re-sequestered along with that from wood. Life-cycle assessment is an accounting method, which treats 'bio' CO_2 differently to 'fossil' CO_2.
[7] Real-world measurements suggest an S-curve, but this should not affect results significantly, if the entire relaxation period is considered.

1.4.2 What is the relaxation period? What is the time horizon?

Answers to these two are critical and not obvious. For both we have defined 'base case' definitions, which seem most reasonable. We also have examined sensitivities to those.

According to (Müller-Wenk and Brandao, 2010, Table 2, p 178), the relaxation time for a tropical forest (to cropland) is 62-65 years. A tropical forest is the most likely setting associated with traditional cooking (see section 1.5), so a relaxation time of 63.5 years has been chosen for the base case.

Choosing a time horizon is a more difficult question. This is also addressed by (Müller-Wenk and Brandao, 2010, p 174), who refer to the time horizon as a 'cut off point': "As the global warming effect of a CO_2 quantity depends on its average stay in air, we want to find out…the average time a CO_2 molecule stays in air. A meaningful average can be calculated only if the curve is cut off after a finite number of years, which means that the climatic influence of CO_2 after this cut-off point is considered to be negligible. A cut-off at year 100 would result in a mean CO_2 stay in air of 47.5 years, while a cut-off at year 500 gives a mean stay in air of 157 years. The choice of this cut-off point should be such that comparisons with CO_2 originating from land use are not heavily distorted; it can be shown that a cut-off at year 100 would be too short, unduly favouring carbon from fossil combustion, so that we prefer a cut-off at 500 years."

Clearly, a longer time horizon favours wood, and a shorter one favours LP Gas. Unlike (Müller-Wenk and Brandao, 2010), who apparently want to favour bio over fossil fuels, this analysis is aimed at finding results that do not favour a particular fuel type, but instead, sensibly inform policy. To that end, there seem to be three choices of time horizon:

■ **Equal to the relaxation period**, i.e. the time required for the forest to return to its state of immediately pre-harvest. For a tropical forest, this is 63.5 years (Müller-Wenk and Brandao, 2010, Table 2, p 178).

■ **Linked to a policy target**, say the 80% carbon reduction by 2050, agreed by the G8 nations in 2009. This gives a time horizon of 2050-2013, or 37 years.

■ **100 years**, the time horizon typically used in carbon footprints.

For the base case, we have used the 63.5 year cut off for a tropical forest. The reason is that this is the time required for the forest to return to its incipient state. This choice is justified by the 'Sustainability criteria for bioenergy' as proposed for ISO 13065 (Corr, 2013), which says:

If the production of a bioenergy product is linked to specific time periods (e.g., seasonal products can range from annual grasses and crops to short- and long-rotation forest), the assessment of GHG emissions and removals should cover the relevant period in the life cycle of the product.

■ *For perennial crops the time period for assessment of the GHG emissions and removals including carbon stock change shall consider at least one entire rotation period.*

■ *The rotation period for perennial crops and forest can range from a few years to more than 100 years. Therefore, it may be necessary to extrapolate emissions and removals if data is not available for the full rotation period. It is essential to document and justify the assumptions and procedures used to estimate the emissions and removals.*

As sensitivities, we have also examined other time horizons and relaxation periods.

1.4.3 Product vs waste/residue wood

Clearly, not all wood used in traditional cooking is a product, i.e. intentionally produced for use in this application. Some is waste or residue that would be disposed or would decompose if not used.

Hard data on the actual split in volumes, for wood used as fuel and for wood used otherwise, are sparse, and hypotheses differ. Researchers such as (Nagothu, 2001) postulate that wood used as fuel comes mainly from residues, whereas researches such as (Sharma et al., 2009) contend that it is mainly harvested from a standing forest. Both sides probably are right: in certain areas, that is. What is lacking is a regional or global view – except in the case of India, where (Reddy and Srinivas, 2009) have estimated a 50/50 split between wood produced as a product or byproduct for fuel and wood fuelled as a residue.

In the base case, we have assumed 100% product wood, so that the carbon effects of other factors are highlighted. In the sensitivities, other percentages are assessed. Obviously, at 100% residue or waste, the footprint of wood cooking would be zero.

1.4.4 Base case results

The net carbon emissions are calculated by integrating the area above the curves (Figure 2). In the base case, this comes out to 21.544 CO_2 tonne-years for wood and 7.185 CO_2 tonne-years for LP Gas.

Figure 2: Net carbon emissions for 1 GJ delivered heat, wood vs LP Gas, base case
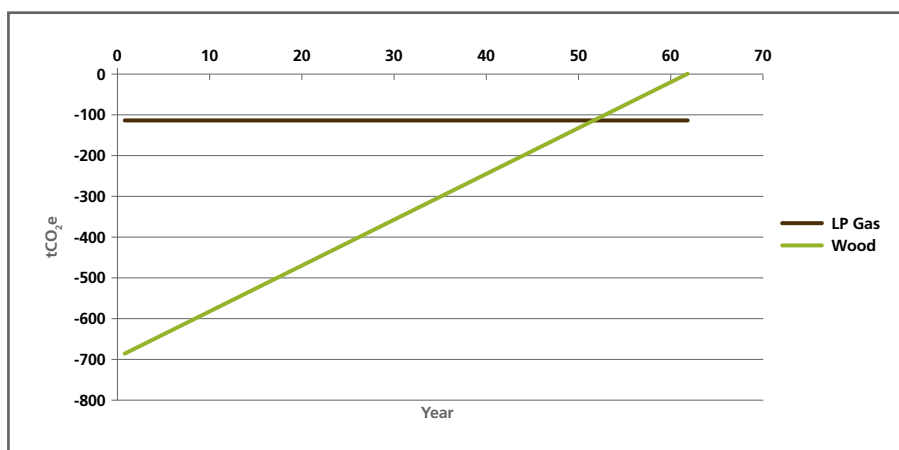
Switching from harvested wood to LP Gas reduces net carbon emissions by

67%

1.4.5 Sensitivities

As the preceding text foreshadows, there are a number of important sensitivities to this analysis, so these have been calculated with respect to the base case. Except for two, the descriptions (Table 2) should be self-explanatory. One exception is the 'soil carbon' scenario. The base case assumes no emissions of soil carbon occur in wood harvesting; the sensitivity assumes that 10% of soil carbon is emitted (and then re-sequestered over the relaxation period) during harvest. The other exception is the 37-year time horizon.

This is chosen, because 2050 – the target date for 80% carbon reductions agreed by the G8 nations – is 37 years away from now.

Not too surprisingly, the greatest sensitivities are to: time horizon, and the use of residue or waste wood. The latter is the greatest sensitivity of all, because by life-cycle accounting convention, waste/residue wood is carbon neutral. At a two-thirds:one-third mix of waste and product wood, the wood emissions are equal to those of LP Gas.

Table 2: Net carbon emissions for 1 GJ delivered heat, wood vs LP Gas, sensitivities

| Scenario	Net carbon emissions CO_2 t-years		Carbon reduction, wood to LP Gas switch
	Wood	**LP Gas**	
Base case	-22'246	-7'419	67%
Time horizon			
Base case 63.5 years	-22'246	-7'419	67%
37 years	-18'168	-4'323	76%
100 years	-14'344	-11'683	19%
Relaxation time			
Base case 63.5 years	-22'246	-7'419	67%
Temperate forest, 74 years	-25'925	-8'646	67%
Boreal forest, 238 years	-83'379	-27'806	67%
Soil carbon, 10% emission			
Base case 0%	-22'246	-7'419	67%
10%	-26'273	-7'419	72%
Wood stove efficiency			
Base case 15%	-22'246	-7'419	67%
10%	-33'369	-7'419	78%
20%	-16'685	-7'419	56%
Residue or waste wood			
Base case 0%	-22'246	-7'419	67%
50% waste wood	-11'123	-7'419	33%
66.7% waste wood	-7'419	-7'419	0%

1.5 A consequential view

As noted above (section 1.2), the analysis so far assumes an 'either or' choice, i.e. people will use either wood or LP Gas as cooking fuel. However, this choice is not shown explicitly in the modelling. So the results have been re-plotted (Figure 3) in a 'consequential' fashion to make that baseline explicit.

Figure 3: Net carbon emissions for 1 GJ delivered heat, wood vs LP Gas, modelled consequentially
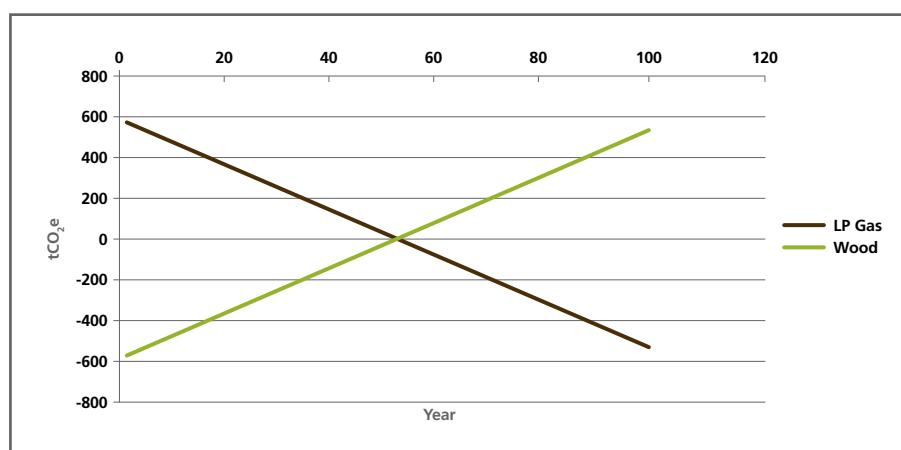
For LP Gas, the net emissions start off positive, because the 700.7 kg CO_2/GJ of wood emission has been avoided; only the 116.8 kg CO_2/GJ of LP Gas emissions have been made. This diminishes over time, as CO_2 is steadily sequestered into the forest. For wood, the function is inverted. This method of presentation (Figure 3) clearly shows the short-term benefits of switching to LP Gas. After 100 years, net emissions for LP Gas are slightly positive (less global warming) and for wood are slightly negative (more global warming). The nets become equal at 105 years.

So again, the key sensitivity to the analysis is the time horizon. At 100 years or less, LP Gas is the lower carbon choice. At more than 100 years, wood becomes more attractive.

1.6 Implications for energy policy

Nearly half of the world's 7.1×10^9 people still use the traditional-biomass method of cooking. The greatest numbers of these are in China, India, Sub-Saharan Africa and Southeast Asia, and many of these are heavily reliant on forest wood, i.e. wood produced not as a residue or waste but a product (Table 3).

Table 3: Biomass cooking and wood harvested for fuel in the developing world (approx. year 2000)

Sources: (IEA, 2002, p 391), (Arnold et al., 2003, Table 4, p 12)

Country	People cooking with biomass, Millions	% of population	% Fuelwood from forest
China	706	56	74
Indonesia	155	74	35
Other East Asia	137	37	60-90
India	585	58	51
Other South Asia	128	41	15-75
Latin America	96	23	NA
N Africa, Middle East	8	0.05	NA
Sub-Saharan Africa	575	89	NA
Developing countries total	**2,390[8]**	**52**	**NA**

The IEA and other sources imply that the vast majority of this cooking, in numbers of people and in volume of fuel, is with wood (a significant portion of that converted to charcoal), but precise figures are not specified. (Charcoal, although easier to use than wood, is much higher in carbon emissions (Johnson, 2009a), but this has not been assessed in this analysis.) Reliance on biomass continues to increase: the IEA projects the number of people cooking with it to rise 9% from 2000-2030 to 2.6×10^9. Major declines in Latin America, Indonesia and China will be more than offset by gains in India, South Asia and Africa.

For areas that use more than one-third *product* wood, i.e. stemwood deliberately harvested for use as fuel, there are significant carbon savings to be achieved from a switch to LP Gas. If they are using half product, half residue/waste, a carbon savings of one-third can be realised. At 100% product wood, a switch to LP Gas can eliminate two-thirds of the net carbon emissions.

The International Energy Agency foresees a major change in developing-world energy use over the coming two decades. Its 'Universal Modern Energy Access Case' (UMEAC) projects a major shift in cooking, from biomass to LP Gas. By 2015, 445 million people will convert some of their biomass consumption for cooking to LP Gas, by 2030 another 730 million people will follow. This would amount to a saving of 274 million tonnes of CO_2 per year, which is roughly equal to the national CO_2 emissions from Taiwan or Thailand in 2011.

By 2015, says the IEA,

445 million people will convert some of their biomass consumption for cooking to LP Gas, by 2030 another 730 million people will follow.

[8] The IEA's current estimate is higher, 2,700 million.

2.0 Avoiding deforestation by substituting LP Gas for wood

Some 540 million households around the world, about 2.7×10^9 people, use biomass to fuel their cooking. Perhaps half of these use wood intentionally harvested for fuel that could be used for other purposes or simply left standing, while the other half use residues such as dung, rice husks or sticks. This paper estimates the deforestation impact of substituting LP Gas for wood in traditional cooking. Supplying this wood demands the annual harvest of 2.4 million hectares of forest. If this were instead supplied by an equivalent amount of liquefied petroleum gas (LP Gas), 43 million tonnes, 2.4 million hectares of forest would be spared annually – equivalent to nearly half the rate of global deforestation. At a more personal scale, switching 100 households from consuming 200 tonnes of harvested wood a year to 1.8 tonnes of LP Gas would annually save one hectare of forest. Each household would save about 100 square metres of forest. Seen at user scale, a typical 13-kg cylinder of LP Gas would avert deforestation of a 7 m² forest area.

2.1 Introduction: cleaner cooking and deforestation

Bringing cleaner cooking to the developing world has in the past decade gained ever increasing attention from the developed world. Organisations such as the Global Alliance for Clean Cookstoves[9] and the National Biomass Cookstoves Initiative[10] (Venkataraman, et al., 2010) have been created to combat the negatives of cooking with traditional cookstoves and open fires. The International Energy Agency (IEA) has proposed a 'Universal Modern Energy Access Case' (IEA, 2010) (IEA, 2012), referred to as UMEAC, that would extend clean cooking (and electrification) to the entire world by 2030.

This traditional-style cooking has three primary negatives. One is economic disadvantage to its practitioners. Traditional-cooking households spend significant (and increasing) amounts of their time collecting fuel, time that could be more productively spent in other types of work. Another is injury and disease. Carrying wood exposes carriers to potential assault by humans or animals, plus bodily damage from the strain. Ailments such as asthma, bronchitis, child pneumonia, lung cancer, chronic obstructive pulmonary disease, heart disease, as well as low birth-weight in children can be caused by chronic exposure to the exhausts of traditional cookers. Then there are environmental damages: excess emissions of global warmers carbon-dioxide and black carbon; and deforestation.

This paper focuses on the final, perhaps least researched in this respect, of those negatives. Deforestation is a well-recognised problem, and is actually a proxy for a number of problems. Probably the most prominent are carbon depletion, desertification, habitat endangerment (reduction of biodiversity), impairment of social amenity, soil erosion and threat to local livelihoods (FAO, 2010). For example, habitat endangerment is documented by (Bearer et al., 2008), who report that wood collection destroys habitat suitable for giant pandas, a well-known endangered species.

The link between deforestation and traditional cooking was first highlighted in the literature by Erik P Eckholm, who wrote that "firewood is the main source of energy for fuel used by the majority of people today, but in many parts of the world it is becoming harder to find or disappearing with use" (Eckholm, 1975, p 31). The logical policy response, Eckholm contended, was tree planting on a "massive scale", and this was attempted under a *Tropical Forestry Action Plan* launched in 1985 by the United Nations' Food and Agricultural Organisation. Under this action plan, tree-planting projects proliferated. Most of them, such as India's Social Forestry programme, focused on community woodlot planting (Arnold, et al., 2003, pp 4-5). Unfortunately, for various reasons, "these did little to augment fuelwood supplies for rural

Ailments such as asthma, bronchitis, child pneumonia, lung cancer, chronic obstructive pulmonary disease, heart disease, as well as low birth-weight in children can be caused by chronic exposure to the exhausts of traditional cookers.

users", and even in urban areas, "shifts away from domestic woodfuel use were not taking place on a very large scale" (Arnold, et al., 2003, p 5).

Partly because of this failure, and also thanks to increasing recognition of traditional cooking's other negatives (noted above), development-policy over the past decade has moved somewhat away from tree-planting toward a greater focus on two other targets: a) substituting other fuels for wood in cooking, and b) improving cookstove performance, regardless of fuel, in terms of fuel efficiency, emissions, durability and safety (Arnold, et al., 2003, p 7) (DfID, 2002) (ISO, 2012) (Maes and Verbist, 2012).

One option is to switch from wood to another fuel, for instance liquefied petroleum gas, commonly known as LP Gas (Thompson, et al., 2011). Clearly, this option meets the criteria of large increases in combustion efficiency, fuel efficiency, or both, proposed by (Ruiz-Mercado, et al., 2011, p 7557). This paper evaluates LP

Gas-switching further, on another important criterion: avoiding deforestation.

Two other studies have posited a link between LP Gas substitution of wood and slowing or reversing deforestation. One, from (Nautiyal and Kaechele, 2008), reports on a Himalayan district where LP Gas substitution increased the health of adjacent forests. Another documents an area in Southeast China, where substitution of wood has "unexpectedly caused significant progress in hilly ecosystem restoration, particularly in mitigation of soil erosion and forest degradation" (Wang et al., 2012). However, neither of these studies nor others identified in a literature search identified any studies such as this paper, which quantifies the relation of fuel switching and deforestation.

2.2 Method

This paper estimates the deforestation impact of substituting LP Gas for wood in traditional cooking. It does so by use of two calculation models, which both use inputs from the public domain. In broad terms, the method is similar to that of life cycle assessment.

First is a model of avoided deforestation model on a micro scale. It models consumption of

wood and LP Gas for cooking, normalised to an average household in the developing world, and relates this to avoided deforestation through substitution of wood by LP Gas. Second is an avoided deforestation model on a macro scale. It extrapolates the micro model to a global scale and compares it to prevailing deforestation rates.

2.3 Avoided deforestation, on a micro-scale

This model (Table 4) develops a carbon-emissions equivalent for wood in cooking, normalised to an average household in the developing world. This is then related, by forest carbon stock, to deforestation caused by consumption of wood.

The three elements of the model (Table 4), shaded blue, red and green, are presented respectively in more detail in the following three subsections.

Table 4: Avoided deforestation, modelled on a micro scale

Quantity	Unit	Item	Reference
5	GJ/yr	Average household cooking, useful energy consumed	(World Bank, 2006, p 39)
2	t	Fuelwood/household, 15% moisture, traditional stove[11]	(World Bank, 2006, p 39)
15%		Moisture, wet basis, in the wood	
50%		C content in wood, bone dry	Numerous, confirmed by (Lamlom and Savidge, 2003)
0.85	t/yr	C from combustion	
86	t C/ha	Above ground forest C, global midpoint	(WBGU, 1998, p 48)
101	Households	Use 1 ha of forest, above ground	
99	m²	forest saved per household to LP Gas	
180	kg/yr	LP Gas, average household cooking (for 5 GJ useful energy)[12]	(World Bank, 2006, p 39)
18	t	Avoided deforestation, amount of LP Gas to save 1 ha of forest	
7	m²	Avoided deforestation, per 13-kg cylinder of LP Gas	

2.3.1 Carbon emissions from cooking with wood, in developing-world households

The figures (Table 4) for average household useful-cooking energy (5 GJ/year) as well its conversion to wood quantity (2 tonnes) are taken from (World Bank, 2006, p 39).

The average consumption of LP Gas, 180 kg/household-year, or 36 kg/person-year, varies significantly from the 22 kg/person-year quoted by the IEA (IEA, 2006, p 15) (IEA, et al., 2010, p

22). This is not a disagreement, rather a case of different definitions. The 36-kg figure applies if the household cooks only with LP Gas. The 22-kg figure is an estimate of LP Gas usage in typical households, which often use multiple cooking fuels (World Bank, 2011b) (World Bank, 2011a). For instance, as (Ruiz-Mercado, et al., 2011) reports, families in Mexico's highlands typically use four different cookers: a three-stone fire, a Patsari stove, an LP Gas stove and a microwave oven. The first two burn biomass to prepare traditional

[11] Assumes about 16% thermal conversion, wood
[12] Assumes about 60% thermal conversion, LP Gas

240 million

households converted to LP Gas could save 2.37 million hectares of forest, IE 46% of annual net global deforestation.

foods such as tortillas and tamales; LP Gas is used for soups, meats and re-heating; the microwave is used for re-heating and making popcorn.

A moisture content of 15% is typical for air-dried wood. This equates[13] to a lower-heating-value of 16 MJ/kg, which is within the normal range of heating values – 15-20 MJ/kg – reported for air-dried wood. The conversion efficiency defined by the World Bank for the traditional wood stove is 15%, which is at the high-end of the 6-16% range for traditional cookstoves in India reported by (Smith, et al., 2000).

Carbon content of wood fuel is assumed to be the rule-of-thumb value of 50% of dry weight. Two papers (Lamlom and Savidge, 2003) (Martin and Thomas, 2011) have shown that that in actual practice there is a variation of about + 3% around 50%. For the accuracy of this analysis, 50% is therefore a reasonable assumption. The conversion, then, is 2 t wood x (1-15%) x 50% carbon = 0.85 t carbon passes

through the average household per year as wood cooking fuel.

2.3.2 Carbon content of forests

In the 1990s a 'Scientific Advisory Council of Global Environmental Change' to the German federal government was charged by the-then Environment Minister, Angela Merkel, with conducting a special audit of biological sources and sinks of carbon dioxide. The audit was published in June 1998 (WBGU, 1998).

In its work the Council compiled, from various sources including the Intergovernmental Panel on Climate Change, a compendium of forest carbon-concentrations for various regions and countries (WBGU, 1998, Appendix, Table 2, p 48). The global midpoint for above-ground concentration is 86 t C/hectare, with regional values ranging from 28-174 t C/hectare. (Below-ground concentrations are much higher; the global midpoint is 189 t C/hectare.) For this estimate, we have used the above-ground midpoint of 86 t C/hectare.

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[13] Calculated according to GJ/tonne = 19.2 - (0.2164*MC), where MC is the moisture content in percent of total weight, as reported at http://www.woodenergy.ie/frequentlyaskedquestions/.

2.3.3 Equivalent deforestation, actual or avoided by LP Gas substitution

Dividing the previous two results into each other gives the following finding: 101 average households consume 1 hectare of above-ground vegetation of an average forest to fuel their cooking for one year. This equates to 99 m^2 of forest per year.

What if that wood is substituted by LP Gas and therefore allowed to remain as forest? Using the same data source as for wood (World Bank,

2006, p 39), the equivalent amount of LP Gas needed to supply the 5 GJ of cooking is 180 kg. (This presumes 60% stove efficiency and a lower-heating value for LP Gas of 45.9 MJ/kg, both of which are consistent with normal reported ranges.)

So, 18 t of LP Gas, if used to replace wood, would avert 1 hectare of deforestation, or 1 t would avert 0.55 hectares of deforestation. Seen at user scale, a typical 13-kg cylinder of LP Gas would avert deforestation of a 7 m^2 forest area.

2.4 Avoided deforestation, on a macro-scale

This macro model (Table 5) extrapolates the micro model to a global scale, and compares it to prevailing deforestation rates.

The four elements of the model (Table 5), shaded red, blue and green, are presented respectively in more detail in the following three subsections.

Table 5: Avoided deforestation, modelled on a macro scale

Quantity	Unit	Item	Reference
2.679	109	People using biomass fuels, global	(IEA, et al., 2010), p 9
5	people	Average household size, developing world	(Bongaarts, 2001)
536	mln	Households using biomass fuels, global	
50%		Households using product/byproduct wood	(Reddy and Srinivas, 2009, p 997)
268	mln	Households using product/byproduct wood	
48	mln	t LP Gas to replace product/byproduct wood	
2.65	mln	ha forest saved	
5.21	mln	ha deforestation/yr, 2000-2010	(FAO, 2010, p xxviii)
51%		Deforestation averted/yr	

2.4.1 Households cooking with traditional biomass

Nearly one-third of the world's 7.1 x 10^9 people still use the traditional-biomass method of cooking. The greatest numbers of these are in China, India, Sub-Saharan Africa and Southeast

Asia, and many of these are heavily reliant on forest wood, i.e. wood produced not as a residue or waste but a product (Table 3).

Table 6: Biomass cooking and harvested fuelwood in the developing world
(approx. year 2000)

Sources: (IEA, 2002, p 391), (Arnold et al., 2003, Table 4, p 12)

Country	People cooking with biomass, Millions	% of population	% Fuelwood from forest
China	706	56	74
Indonesia	155	74	35
Other East Asia	137	37	60-90
India	585	58	51
Other South Asia	128	41	15-75
Latin America	96	23	NA
N Africa, Middle East	8	0.05	NA
Sub-Saharan Africa	575	89	NA
Developing countries total	**2,390[14]**	**52**	

[14] The IEA's current estimate is higher, 2,700 million.

The IEA and other sources imply that the vast majority of this cooking, in numbers of people and in volume of fuel, is with wood (of which significant amounts have been converted to charcoal), but precise figures are not specified. Reliance on biomass continues to increase: the IEA projects the number of people cooking with it to rise 9% from 2000-2030 to 2.6×10^9. Major declines in Latin America, Indonesia and China will be more than offset by gains in India, South Asia and Africa.

If all households using biomass were to cook with wood, total consumption would be 480 million household x 2 t wood/household = 960 million t wood. Wood densities vary, but using a representative 0.6 t/m³ density for chopped, stacked logs with 15% moisture (AEBIOM, 2008) yields a consumption volume of 1,600 million m³. This correlates reasonably with an estimate of developing-world wood consumption as fuel of 1,591 million m³ (Arnold, et al., 2003, Table 2, p 9).

2.4.2 Wood supply: residue or waste versus product or byproduct
The macro model posited in this paper assumes that using biomass residues or wastes as fuel does not contribute to deforestation. This assumption is common to analyses such as this, to life cycle assessments in general and has even been incorporated in legislation (European Commission, 2009). The most common example is carbon footprints: fuels derived from residues or wastes usually are considered to be carbon neutral (Johnson, 2009b). Conversely, the macro model assumes that product (or byproduct) wood does contribute to deforestation.

Hard data on the actual split in volumes, for wood used as fuel and for wood used otherwise, are sparse, and hypotheses differ. Researchers such as (Nagothu, 2001) postulate that wood used as fuel comes mainly from residues, whereas researches such as (Sharma, et al., 2009) contend that it is mainly harvested from a standing forest. Both sides probably are right: in certain areas, that is. What is lacking is a regional or global view – except in the case of India, where (Reddy and Srinivas, 2009) have estimated a 50/50 split between wood produced as a product or byproduct for fuel and wood fuelled as a residue. The macro model in this paper (Table 5) adopts that 50/50 estimate. To some extent, it is corroborated by the estimates of (Arnold, et al., 2003, Table 4, p 12).

2.4.3 Deforestation rates, and LP Gas aversion of deforestation
For the 50% of wood produced as a product or byproduct, an equivalent amount of LP Gas is 180 kg/household (Table 4) x 480 million household x 50% = 43 million t LP Gas. This amounts to about 19% of current global LP Gas production (Thompson, et al., 2011), but this percentage will decline sharply over the coming decade, as significant new sources in the Middle East, Russia and the USA come onstream. Applying the conversion of 101 households/hectare (Table 4) to 240 million households equals 2.37 million hectares of forest that annually would not be consumed for fuel, if this were substituted with LP Gas.

As a benchmark, this is equivalent to 46% of annual net global deforestation over the 2000-2010 period, 5.21 million hectares (FAO, 2010). Obviously, deforestation does not progress at equal rates everywhere, but with the exceptions of China and India the developing world is clearly in deficit (Table 7). Even in the cases of China and India, greater rates of afforestation would be desirable, to recompense massive deforestations in earlier times.

Table 7: Deforestation and afforestation in the developing world
(2000-2010, 1,000 hectares/year)

Source: (FAO, 2010, Tables 2.4, 2.5 and 2.6)

Country	Change in forest area
China	+2,986
Indonesia	-498
South and Southeast Asia	-677
India	+304
Latin America	-4,245
N Africa	-41
Sub-Saharan Africa	-3,373

A developing world household consumes
2 tonnes of wood per year which is the equivalent
of approximately

10 trees or 180 kg of LP Gas*

What if this same logic is applied to the 'Universal Modern Energy Access Case' (UMEAC) proposed by the IEA? Under UMEAC, uptake of LP Gas would be more modest than the full replacement modelled above. By 2015, 445 million people will convert some of their biomass consumption for cooking to LP Gas, by 2030 another 730 million people will follow suit. But, rather than shifting all cooking to 180 kg LP Gas/ household-year, they would shift part of it to LP Gas, 110 kg/household year. Using the same 50/50 split of product and residue, this would spare 440,000 hectares/year of forest by 2015, and 1.2 million hectares/year by 2030, which amount to, respectively, 8% and 22% of annual, global, net deforestation in 2000-2010.

*Tree sizes, types and planting densities vary considerably. This figure is based on a broad average and could be revised up or down depending on the situation.

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