Co-benefits of Reducing Short-lived Greenhouse Pollutants or PICs and the Poor

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University of California, Berkeley
1990: 85%: 700 million people using solid fuels

2010: 60%: 700 million people

~1980 700 million people in entire country

700 million people in the Chulha Trap
Energy flows in a well-operating traditional wood-fired Indian cookstove (chulha)

A Toxic Waste Factory!!

Typical biomass cookstoves convert 6-30% of the fuel carbon to toxic substances + methane

- Into Pot: 2.8 MJ (18%)
- In PIC: 1.2 MJ (8%)
- Waste Heat: 11.3 MJ (74%)

PIC = products of incomplete combustion = CO, HC, C, etc.

Source: Zhang, et al., 2000
Nominal Combustion Efficiencies in Indian Stoves

Smith, et al., 2000

- Gas: 99% (98-99.5)
- Kerosene: 97 (95-98)
- Wood: 89 (81-92)
- Crop residues: 85 (78-91)
- Dung: 84 (81-89)

Recent data from Haryana households

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Angithi</td>
<td>2</td>
<td>0.86 (±0.04)</td>
</tr>
<tr>
<td>Fixed Chula w/o Chimney</td>
<td>16</td>
<td>0.92 (±0.01)</td>
</tr>
<tr>
<td>Haro</td>
<td>5</td>
<td>0.89 (±0.02)</td>
</tr>
<tr>
<td>Phillips</td>
<td>13</td>
<td>0.94 (±0.01)</td>
</tr>
</tbody>
</table>
Toxic Pollutants in Biomass Fuel Smoke from Simple (poor) Combustion

• Small particles, CO, NO₂
• Hydrocarbons
  – 25+ saturated hydrocarbons such as n-hexane
  – 40+ unsaturated hydrocarbons such as 1,3 butadiene
  – 28+ mono-aromatics such as benzene & styrene
  – 20+ polycyclic aromatics such as benzo(α)pyrene
• Oxygenated organics
  – 20+ aldehydes including formaldehyde & acrolein
  – 25+ alcohols and acids such as methanol
  – 33+ phenols such as catechol & cresol
  – Many quinones such as hydroquinone
  – Semi-quinone-type and other radicals
• Chlorinated organics such as methylene chloride and dioxin

Typical chulha releases 400 cigarettes per hour worth of smoke

Source: Naehler et al, J Inhal Tox, 2007
First person in human history to have her exposure measured doing the oldest task in human history

~5000 ug/m³ during cooking
>500 ug/m³ 24-hour

Emissions and concentrations, yes, but what about exposures?

Kheda District, Gujarat, 1981

Millions Dead: How Do We Know and What Does It Mean? Methods Used in the Comparative Risk Assessment of Household Air Pollution

Kirk R. Smith,¹,* Nigel Bruce,²,* Kalpana Balakrishnan,³ Heather Adair-Rohani,¹ John Balmes,¹,⁴ Zöe Chafe,¹,⁵ Mukesh Dherani,² H. Dean Hosgood,⁶ Sumi Mehta,⁷ Daniel Pope,² Eva Rehfuess,⁸ and others in the HAP CRA Risk Expert Group¹
## The Energy Ladder: Relative Pollutant Emissions Per Meal

<table>
<thead>
<tr>
<th></th>
<th>Biogas</th>
<th>LPG</th>
<th>Kerosene</th>
<th>Wood</th>
<th>Roots</th>
<th>Crop Residues</th>
<th>Dung</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0.1</td>
<td>1.0</td>
<td>3</td>
<td>19</td>
<td>22</td>
<td>60</td>
<td>64</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>0.3</td>
<td>1.0</td>
<td>4.2</td>
<td>17</td>
<td>18</td>
<td>32</td>
<td>115</td>
</tr>
<tr>
<td>PM</td>
<td>2.5</td>
<td>1.0</td>
<td>1.3</td>
<td>26</td>
<td>30</td>
<td>124</td>
<td>63</td>
</tr>
</tbody>
</table>

Smith, et al., 2005
State and national household concentrations of PM$_{2.5}$ from solid cookfuel use: Results from measurements and modeling in India for estimation of the global burden of disease

Kalpana Balakrishnan$^1$, Santu Ghosh$^1$, Bhaswati Ganguli$^2$, Sankar Sambandam$^1$, Nigel Bruce$^3$, Douglas F Barnes$^4$ and Kirk R Smith$^5$
State-wise estimates of 24-h kitchen concentrations of PM2.5 in India

Solid-fuel using households

Balakrishnan et al. 2013
Diseases for which we have sufficient epidemiology

ALRI/Pneumonia
COPD
Lung cancer (coal)
Lung cancer (biomass)
Cataracts
Ischemic heart disease
Stroke

These diseases are included in the 2010 Comparative Risk Assessment (released in 2012)
Large areas of rural India & China have high ambient air pollution

20-month average ground-level PM2.5 from satellite data

Non-urban outdoor pollution is substantial
Relative contribution of household cookstoves to outdoor particle pollution ~26% in India

Chafe, et al., 2014
Total Burden of HAP in India

- About 1.15 million premature deaths including the contribution to outdoor
- About twice the impact of the rest of ambient air pollution
- Considerable uncertainty, but not extending to small effects.
GREENHOUSE GASES FROM BIOMASS AND FOSSIL FUEL STOVES IN DEVELOPING COUNTRIES: A MANILA PILOT STUDY


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Applied Science Division, Bldg. 90, Room 3120, 1 Cyclotron Road
Berkeley, California 94720, USA

(Received in USA 26 November 1991; accepted 15 April 1992)
Greenhouse warming commitment per meal for typical wood-fired cookstove in India

Wood: 1.0 kg
454 g Carbon

CO2 Carbon: 403 g

Methane Carbon: 3.8 g

Other GHG Carbon
Carbon Monoxide: 38 g
Hydrocarbons: 6.3 g
131 g
69 g

Nitrous Oxide
0.018 g

Global warming commitments of each of the gases as CO₂ equivalents

Source: Smith, et al., 2000
## Radiative forcing by emissions and drivers

<table>
<thead>
<tr>
<th>Emitted compound</th>
<th>Resulting atmospheric drivers</th>
<th>Radiative forcing relative to 1750 (W m⁻²)</th>
<th>Level of confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>CO₂</td>
<td>1.68 [1.33 to 2.03]</td>
<td>VH</td>
</tr>
<tr>
<td>CH₄</td>
<td>CO₂, H₂O, O₃, CH₄</td>
<td>0.97 [0.74 to 1.20]</td>
<td>H</td>
</tr>
<tr>
<td>Halo-carbons</td>
<td>O₃, CFCs, HCFCs</td>
<td>0.18 [0.01 to 0.35]</td>
<td>H</td>
</tr>
<tr>
<td>N₂O</td>
<td>N₂O</td>
<td>0.17 [0.13 to 0.21]</td>
<td>VH</td>
</tr>
<tr>
<td>CO</td>
<td>CO₂, CH₄, O₃</td>
<td>0.23 [0.16 to 0.30]</td>
<td>M</td>
</tr>
<tr>
<td>NMVOC</td>
<td>CO₂, CH₄, O₃</td>
<td>0.10 [0.05 to 0.15]</td>
<td>M</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrate, CH₄, O₃</td>
<td>-0.15 [-0.34 to 0.03]</td>
<td>M</td>
</tr>
<tr>
<td>Aerosols and precursors</td>
<td>Mineral dust, Sulphate, Nitrate, Organic carbon, Black carbon</td>
<td>-0.27 [-0.77 to 0.23]</td>
<td>H</td>
</tr>
<tr>
<td>Cloud adjustments due to aerosols</td>
<td></td>
<td>-0.55 [-1.33 to -0.06]</td>
<td>L</td>
</tr>
<tr>
<td>Albedo change due to land use</td>
<td></td>
<td>-0.15 [-0.25 to -0.05]</td>
<td>M</td>
</tr>
<tr>
<td>Natural</td>
<td>Changes in solar irradiance</td>
<td>0.05 [0.00 to 0.10]</td>
<td>M</td>
</tr>
</tbody>
</table>

### Total anthropogenic RF relative to 1750

- **2011**: 2.29 [1.13 to 3.33] (H)
- **1980**: 1.25 [0.64 to 1.86] (H)
- **1950**: 0.57 [0.29 to 0.85] (M)

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**AR5, WG1**
Unger et al., PNAS, 2010
Unger et al., PNAS, 2010
State-wise estimates of 24-h kitchen concentrations of PM2.5 in India

Solid-fuel using households

Balakrishnan et al. 2013

3 million tons of methane emissions: ~1% of global total
Per Capita Historical Climate Debt: CO$_2$ and Methane

Smith, et al., PNAS, 2013
Historical Climate Debt

(A) $\text{IND}_{\text{CO}_2(f)}$
World RF = 1123 mW/m²
- United States 25.1%
- China 11.1%
- Russian Federation 8.5%
- Germany 5.1%
- Japan 4.8%
- United Kingdom 3.2%
- Other Countries 32.3%

(B) $\text{IND}_{\text{CH}_4}$
World RF = 856 mW/m²
- China 16.4%
- United States 9.6%
- India 8.2%
- Brazil 5.5%
- Russian Federation 7.4%
- Indonesia 3.1%
- Nigeria 1.8%
- Australia 1.7%
- Mexico 1.7%
- Pakistan 1.7%
- Other Countries 42.9%

(C) $\text{IND}_{\text{CO}_2(f)+\text{CH}_4}$
World RF = 1979 mW/m²
- United States 18.4%
- China 13.4%
- Russian Federation 8.0%
- India 5.3%
- Germany 3.5%
- Japan 2.9%
- United Kingdom 2.3%
- Ukraine 2.0%
- Canada 1.8%

(D) LUCF
World RF = 437 mW/m²
- LUCF (18.1% of climate debt from $\text{CO}_2(f)+\text{LUCF}+\text{CH}_4$

Smith, et al., PNAS, 2013
Increasing Prosperity and Development

Decreasing Household Air Pollution

Very Low Income 200 million

Low Income 400 million

Middle Income 400 million

High Income 200 million

Crop Waste

Dung

Solid Fuels

Non-solid fuels

Coal

Kerosene

Liquefied Petroleum Gas

Biogas

Natural Gas

Electricity

Conceptual Indian Energy Ladder

How do we help people move into this realm?

Smith/Pillarisetti, 2014
Diversity of improved cook stoves
Current Health Evidence

• Shows now that even major reductions (<90%) in emissions still lead to small health improvements

• Posing a very large technical challenge to solid fuels to reach 99% or greater reductions over open fires

• This is very difficult with any solid fuel

• But still worth pursuing
Increasing Prosperity and Development

Decreasing Household Air Pollution

Very Low Income
200 million

Low Income
400 million

Middle Income
400 million

High Income
200 million

Ag res-
15%

Non-solid fuels

Elec < 1%

PNG < 1%

Coal – 1%

Kerosene -3%

LPG – 30%

Biogas – 0.3%

Wood – 49%

Solid Fuels

~400

~4

~1.0

Household Energy Ladder in India

Decreasing Household Air Pollution
Carbon Balance in Typical LPG Stove
99.4% combustion efficiency

LPG: 1 kg
825 g Carbon

- CO₂ Carbon: 820 g
- PIC Carbon:
  - CO: 1.1 g
  - CH₄: 0.4 g
  - TNMOC: 3.3 g
- Char/Ash: 0 g

Particle Carbon: 0.1 g

1.0 kg of LPG in this stove would deliver about 23 MJ to the pot

Smith et al., 2005
If 20-year GWPs for GHGs, LPG is roughly equal to renewable wood for cooking.
Indian Energy Ladder

- **Very Low Income (200 million)**
  - **Solid Fuels**
    - **Crop Waste Dung**
  - **Non-solid fuels**
    - **Wood**

- **Low Income (400 million)**
  - **Solid Fuels**
    - **Coal**
  - **Non-solid fuels**
    - **Kerosene**

- **Middle Income (400 million)**
  - **Non-solid fuels**
    - **Biogas**
  - **Solid Fuels**
    - **Liquefied Petroleum Gas**

- **High Income (200 million)**
  - **Electricity**
  - **Natural Gas**
Making the Clean Available

- Incomplete fuel combustion is the enemy
- It has to be very low to reduce combustion particles to health guidelines
- One of the only proven ways to reach near complete combustion in small devices is with gas.
- Although non-renewable, LPG and other gaseous fuels would not add appreciably to global warming.
Conclusions

• It is difficult to burn unprocessed solid fuels completely in simple household-scale devices.

• Consequently, a large fraction of the fuel C is diverted to PIC

• Leading to inefficient use of the primary resource

• And, because of the proximity to population, the PIC seem to be responsible for much ill-health in developing countries.
Conclusions, cont.

• Among climate active PIC, methane holds a unique niche
  – High RF and large emissions: 2nd largest total impact after CO2
  – Largest source of rising global levels of ground-level ozone
  – Relatively short-lived, but long-enough to be globally mixed – can be treated under existing frameworks
  – Two-thirds of its emissions are amenable to control measures using existing technology and policy tools, much at low cost

• Adding in shorter-lived CAPs to climate debt discussions shifts the political landscape – more responsibility to LDCs in the case of methane, but also
  – Controls in LDCs wield greater leverage for making an impact – opportunities are greater and response to them faster than in rich ones

• Plus, for household combustion, nearly all the health benefits accrue locally to the very poorest and most disenfranchised people on the planet
Once global and national markets pick up their portions, local market can pay remainder – fuel savings.

Paying for Rural Energy Development

Global Climate Market

$ per ton-carbon (world carbon market)

National Health “Market”

1-3x $GDP/capita per DALY saved (WHO/IBRD, etc. recommendation)

Local Market

Technology
Laws of Carbon-atmospherics

I. Keep all fossil and forest carbon out of the atmosphere

II. If you cannot do so, the least-damaging form to release is carbon dioxide because all other forms, gas or aerosol, are worse for climate and health.
   – If gases, they eventually turn to CO$_2$ but are worse than CO$_2$ until they do

III. Even renewable (non-fossil) carbon is damaging for climate and health if not released as carbon dioxide.
“Wood is the fuel that warms you twice” - true?

1. Once when you chop it: ~20 kJ/kg
2. Once when you burn it: ~20 MJ/kg
3. When it warms you through radiative forcing in the atmosphere: ~20 GJ/kg
4. And finally, fever from induced respiratory infection due to smoke exposure

Thus, biomass is the fuel that can warm you four times: breaking, burning, forcing, and fever.
Conclusion

If you have to put carbon into the atmosphere, the best form is CO$_2$ – anything else is worse from both climate and health standpoints

or

Get rid of PIC and you make the world a better place
Many thanks

Publications and presentations on website – easiest to just “google” Kirk R. Smith