Atmospheric Pollution Research 2 (2011) 267-274

Atmospheric Pollution Research

www.atmospolres.com

Australian wood heaters currently increase global warming and health costs

Dorothy L. Robinson

National Centre for Rural Greenhouse Gas Research, NSW Department of Industry and Investment, Univ. of New England, Armidale, NSW 2351, Australia

ABSTRACT

Firewood production is often considered to be CO_2–neutral, if the carbon dioxide emitted by burning the wood is absorbed by replacement trees. However, burning firewood in the domestic heaters that are currently available in Australia produces methane and black carbon particles that increase global warming. The aim of this study was to estimate the amount of global warming from wood heating in Australia and evaluate ways in which this might be reduced. Methane from the average wood heater in Brisbane, Perth or Sydney is estimated to cause at least as much global warming as gas central heating an entire house with floor area of 160 m^2. In the colder climates of Canberra and Melbourne, a wood heater in the living area plus supplementary heating in other rooms is also estimated to cause more global warming than gas, or reverse cycle air–conditioning.

Australia's annual contribution to global warming would be reduced by at least 8.7 million tonnes of CO_2–equivalent (the same as removing about 21% of Australian passenger cars from the roads, or generating electricity from 5.8 million household 1 kW rooftop photovoltaic systems) if the 4.5 to 5 million tonnes of firewood currently burned in domestic wood heaters were instead used to replace coal in power stations and domestic wood heaters replaced by gas or reverse cycle air–conditioning. Replacement with pellet heaters would also reduce global warming and the health cost of $PM_{2.5}$ emissions, estimated to exceed \$3 800 per wood heater per year. However, even greater reductions could be achieved if domestic wood heaters were replaced by innovative developments such as solar air heaters or local combined heat and power units that burn cleanly with minimal methane emissions, providing electricity and hot water as well as domestic heating.

Keywords:
Firewood
Wood heating
Carbon
Methane
Global warming

Article History:
Received: 16 September 2010
Revised: 13 January 2011
Accepted: 14 January 2011

Corresponding Author:
Dorothy L. Robinson
Tel: +61-267-701837
Fax: +61-267-701830
E–mail: drd.robinson@gmail.com

doi: 10.5094/APR.2011.033

1. Introduction

Currently, the Australian wood heating industry promotes wood heaters by claiming they cause less global warming than other forms of heating (AHHA, 2010). However, although firewood harvested from a continually renewed supply is considered to be CO_2–neutral (Paul et al., 2006), a Swedish study (Johansson et al., 2004) found that methane emissions from older–style wood–fuelled burners could cause up to twice as much global warming (over the standard 100–year time horizon) as using oil–fuelled heating, whereas modern Swedish designs had much lower methane and particle emissions.

New wood heaters installed in Australian homes have similar emissions to the older–style Swedish models (Meyer et al., 2008), suggesting that, like the older–style Swedish models, they could increase global warming. The aim of this study was to estimate the amount of global warming from wood heating in Australia and evaluate ways in which this might be reduced. Data on methane emissions and firewood use were combined to estimate the total effect on global warming of wood heaters in Australia and facilitate comparison with other forms of heating, including more efficient wood heaters (e.g. pellet heaters), and other uses of biomass.

2. Methods

Published literature was reviewed to obtain estimates by location of Australian firewood consumption, wood heater emissions, as well as comparable data on energy use and greenhouse gas emissions for flued gas heaters and reverse cycle air–conditioning (rcAC).

2.1. Laboratory tests of wood heater emissions

A comprehensive laboratory study (Gras, 2002) measured emissions, for a range of fuels and burn rates, of 4 Australian wood heaters – two freestanding models satisfying the Australian Standard AS4013 (CS/62, 1999), a fireplace insert satisfying AS4013 and a popular well–used heater made in 1985. Tests (mostly of correctly–operated heaters) burning eucalypt hardwoods had average particle emissions of 4.5 g/kg fuel (range 0.2 to 21 g/kg, the latter for the larger freestanding AS4013 heater on low–burn using redgum). The larger AS4013 heater (which had the highest emissions burning eucalypts), was also tested on softwood, for which particle emissions ranged from 7 to 29.4 (mean 15.8) g/kg.

Combustion efficiency (carbon emitted as CO_2, as percentage of total carbon emissions) ranged from about 68% (for the redgum low–burn test emitting 21 g/kg) to 98%. Many different carbon compounds were found in the smoke, including CO_2 (average 2 kg per kg of eucalypt burned, 1.9 for softwood), carbon monoxide (CO, average 120 g/kg for eucalypt, 220 for softwood), methane, acetic acid, formaldehyde, benzene and unspecified Volatile Organic Compounds (VOCs). There was a consistent (negative) relationship between particle emissions and combustion efficiency (Gras, 2002).

Data from the above study (shown in Figure 1) was used to derive the equation used by the Australian Department of Climate

Change (Todd, personal communication) to calculate methane emissions from wood heaters burning eucalypts (DCC, 2009):

CH_4 (g/kg) = 1.495 x particle emissions (g/kg) (1)

A different equation is needed for softwoods, with CH_4 (g/kg) equal to about 2.15 times particle emissions (g/kg, Figure 1).

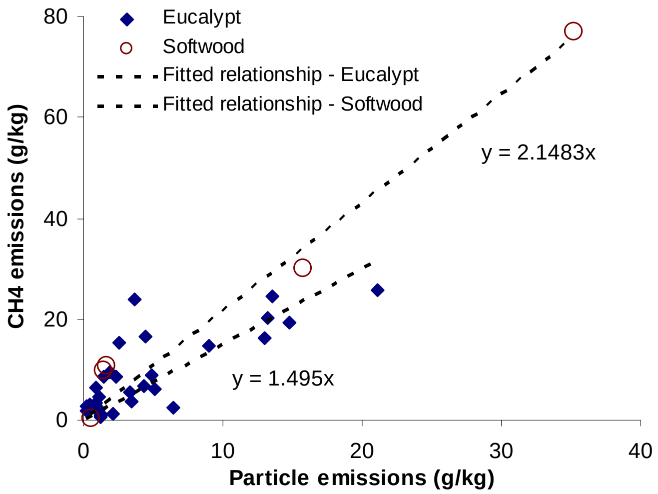

***Figure 1.** Relationship between particle and methane emissions for eucalypts (r=0.78; Gras, 2002) and softwoods (r=0.98 for an Australian heater (Gras, 2002) plus the average modern and three old Swedish burners (Johansson et al., 2004).*

2.2. Household emissions

Australian heaters are designed to pass the AS4013 laboratory test, which unfortunately does not reflect the way heaters are operated in the home environment (Todd, 2008). Consequently, residential emissions are much higher (Meyer et al., 2008). Similar problems were noted in New Zealand (NZ) by Scott (2005) – emissions from 5 heaters installed in people's homes averaged 15.5 g/kg, more than 15 times their AS4013 average of 1.0 g/kg.

Emissions were also measured from 18 AS4013 heaters operated by householders in Launceston, Tasmania (Meyer et al., 2008), where education programs, including a $2 million federally–funded wood–smoke reduction program, had alerted the public to the serious health problems caused by breathing wood–smoke, with 70% of wood–heated households switching to non–polluting heating (DEH & CSIRO, 2005; Meyer et al., 2008). Knowing the health effects of wood–smoke and that their emissions were being measured, the volunteers for this study would have been motivated to take the time and trouble to operate their heaters correctly. Indeed, there was no evidence that heaters were "allowed to smolder overnight; in contrast they appeared to be re–fuelled periodically throughout". Nonetheless, about 15% of fuel carbon was emitted as CO, indicating that the dampers were usually partly or fully closed.

Particle emissions averaged 9.4 g/kg, more than twice the limit specified for the AS4013 laboratory test, twice the average in the comprehensive laboratory study (Gras, 2002), and almost twice the emissions factor (5.5 g/kg) in the National Pollutant Inventory (Meyer et al., 2008). The researchers concluded that the NPI emissions factor should be increased to 10 g/kg. Australian wood heater expert, John Todd, recommended an even higher average of 10–15 g/kg, noting that residents of other Australian cities know little about the health problems of breathing wood–smoke, so in–service emissions would be substantially higher than in Launceston (Todd and Solomon, 2009).

A value of 12.5 g/kg was therefore used as the most plausible average for Australian wood heaters burning eucalypts, leading to the estimate, from Equation (1), of 1.495 x 12.5 = 18.7 grams of methane per kg firewood. This value is in the range (14 to 25 g/kg) reported by Larson and Koenig (1994), and lower than emissions of a carefully–operated new Australian heater burning softwood (30 g/kg; Gras, 2002) or the similar value (32 g/kg; Houck et al., 2008) for older–style US heaters. It is less than a quarter of measured CH_4 emissions (77 g/kg) for an older style Swedish batch–fuelled boiler with particle emissions of 35 g/kg (Johansson et al., 2004), but higher than the estimate of 5.8 g/kg used by Solli et al. (2009) for both old stoves (emitting 40 g $PM_{2.5}$ per kg firewood) and new stoves (6.3 g $PM_{2.5}$ per kg firewood). Solli et al. (2009) sourced their emission factors from Haakonsen and Kvingedal (2001) who cited IPCC (1997). Later guidelines (IPCC, 2006) report higher CH_4 emission factors, ranging from 258 – 2 190 kg/TJ (about 4 – 35 g/kg).

Real–life emissions studies showed that domestic wood heater emissions were grossly under–estimated in Australia (Meyer et al., 2008) and NZ (Scott, 2005). A similar problem was noted in Denmark where Illerup and Nielsen (2004) concluded that $PM_{2.5}$ emissions from residential wood heating were nearly 5 times greater than the latest officially reported estimates. Because residential emissions can differ considerably from laboratory tests, realistic estimates need to be based on measurements of in–service emissions. The estimate of 18.7 g CH_4 per kg firewood, derived from estimated in–service emissions, is both realistic and consistent with published literature estimates.

With an estimated 4.5 to 5 million tonnes of firewood burned in Australia (Paul et al., 2006), estimated CH_4 emissions are 88 800 tonnes, twice the 42 710 tonnes reported in the 2008 Australian National Greenhouse Inventory for CH_4 from residential biomass burning (DCC, 2010), consistent with the new information (Meyer et al., 2008) that measured in–service emissions are much higher than NPI estimates.

2.3. GWP of non–CO_2 greenhouse gases

Table 1 summarizes estimates of global warming potentials (GWP) for methane and CO from the IPCC Fourth Assessment Report (AR4), and also by researchers at NASA (Shindell et al., 2009), who modeled interactions of gases and aerosols and concluded that the effect of methane on global warming has been under–estimated. With current levels of radiative forcing (RF) approaching levels historically correlated with an ice–free planet, Jackson (2009) discussed the likelihood of reaching irreversible points of no return (tipping points), noting that time spans of the order of decades were increasingly relevant. Consequently, 20–year GWP may be more useful indicators of the true effect than 100–year GWP.

Thus the estimate used in this study – 468 g CO_2–eq per kg firewood, calculated by multiplying CH_4 emissions (18.7 g/kg) by the AR4 estimate of methane's GWP (25) – should be considered as conservative. If NASA's estimates of GWP are closer to the correct values, or if a tipping point could be reached in less than 100 years, or if the effect of CO (noted by Meyer et al. (2008) to account for about 15% of fuel carbon i.e. about 200 g CO per kg fuel) is included, the true effect on the climate could be up to 12 times greater.

3. Results and discussion

3.1. CO_2 emissions – central heating

Estimates of the energy required per year to heat a typical Australian house (floor area 160 m^2, insulated ceiling, but not walls) in Australian Capital cities are shown in Table 2. The values (produced by the Australian Consumers Association (ACS, 1999),

***Table 1.** Estimated Global Warming Potentials (GWP) over 20-year and 100-year time horizons for methane (CH_4), carbon monoxide (CO), and CO_2-eq (g) from burning 1 kg firewood in Australia*

	IPCC 4th Assessment Report (AR4)			Shindell et al. (2009) [d]	
	100-year		20-year	100-year	20-year
GWP for CH_4	25	25	72	33	105
GWP for CO	0 [b]	1.9	1.9 [c]	5	19
CO_2-eq of 18.7 g CH_4 + 200 g CO [a]	468	848	1 726	1 617	5 764
Multiple of AR4 with zero CO GWP	1.00	1.81	3.69	3.46	12.33

[a] *Average emissions from burning 1 kg firewood in an AS4013 heater are: 18.7 g CH_4 and 200 g CO (see Sections 2.2 and 2.3).*
[b] *Ignoring CO (not covered by the Kyoto protocol)*
[c] *No 20-year estimate for CO was found in AR4, so the 100-year GWP was used.*
[d] *Shindell et al. (2009) have higher uncertainties (e.g. 25 to 40 for 100-year CH_4 GWP)*

using a greenhouse emissions calculator developed by Sustainable Solutions for Victoria's State Government Environment Protection Authority) range from 4 GJ per year in Brisbane to 40 GJ in Canberra (Table 2).

The accompanying notes explain that energy requirements were calculated from climate information. Winter temperatures in Brisbane (monthly averages, min – max) are 11.6 – 22 °C (June), 10 – 21.9 °C (July) and 10.5 – 23.3 °C (August; BOM, 2010), so homes need to be heated only for short periods of time. Longer periods of heating are required in other cities, according to the climate. Canberra averages 1.3 – 12.5 °C (June), 0.2 – 11.8 (July) and 1.3 – 13.5 (August; BOM, 2010), so its homes require the most heating – 40 GJ, ten times more than Brisbane homes.

The values in Table 2 apply to heating that is switched off when a comfortable temperature is reached. Wood heating cannot be controlled in this way. Once a fire has been lit and loaded with logs, users often turn the air control to its lowest setting (which has the highest particle, CO and CH_4 emissions) letting the fire burn out over the next several hours. Fires are rarely, if ever, extinguished to allow the partially burned logs to be saved for another occasion.

The energy burned in wood heaters must therefore be estimated from average firewood consumption in each capital city (BDA, 2006). The average amount of wood burned per household in Brisbane, Perth and Sydney – 1.1 to 2.5 tonnes (Table 2) – is enough to generate 11 to 24 GJ of heat per year, far more than the 3.6 to 12.2 GJ required to heat a 160 m^2 house with insulated ceiling. In contrast, in the colder climates of Melbourne and Canberra, average firewood consumption (4.3 and 3.7 tonnes) generates 41 and 36 GJ of heat, much closer to the heating needs (34.3 and 39.6, Table 2) of a 160 m^2 house.

A plausible reason why wood consumption in colder areas is closer to heating needs is that heating is used for longer periods of the day, reducing the amount of energy wasted by an appliance that, once lit, produces large quantities of heat on its lowest setting for 6 – 8 hours. Gilmour and Walker (1995) discussed inefficiencies of use, comparing average heating needs (about 3.6 kW) in much colder climates such as Oregon and New York with average heat output from NZ wood–burners – 4.6 kW (16.6 MJ/h) on low burn, and more than 15 kW on high burn.

Even in the two coldest Australian capital cities, Canberra and Melbourne, the energy used to heat the living area is similar to the amount needed to heat an entire 160 m^2 house. Firewood for Canberra and Melbourne has to be transported long distances, so is more expensive per unit of delivered heat than gas or reverse cycle air–conditioning (ACS, 1999). Some households might therefore economize by lighting the wood heater only on days when substantial heat is needed for several hours. Consequently, the values for average wood consumption (Table 2) could under–estimate the amount of fuel burned in houses where the living area has no other heating, and so under–estimate greenhouse emissions in these circumstances.

***Table 2.** Annual heating requirements (GJ) and greenhouse gas emissions (tonnes CO_2-eq) from gas and electric central heating and wood heating in Australian cities*

City	Central heating (GJ)	Flued gas CO_2 tonnes	Reverse cycle AC CO_2 tonnes	Wood (living area) tonnes burned (GJ)	usage efficiency (%)	CH_4 CO_2-eq tonnes (A)	CO_2 tonnes (B)	Supp. heat. tonnes CO_2 (C)	Wood Sustainable source A+C	Total A+B+ C
Brisbane	3.6	0.3	0.3	1.1 (11)	14	0.5	2.2	0.2	0.7	2.9
Perth	6.8	0.5	0.6	2.5 (24)	11	1.2	5.0	0.4	1.5	6.5
Sydney	12.2	0.9	1.0	1.9 (18)	27	0.9	3.8	0.7	1.6	5.4
Melbourne	34.3	2.6	3.6	4.3 (41)	33	2.0	8.6	2.5	4.5	13.1
Canberra	39.6	3.0	3.1	3.7 (36)	45	1.7	7.4	2.2	3.9	11.3
Weighted average [a]	17.6	1.3	1.6	2.7 (26)	26	1.3	5.4	1.1	2.4	7.7

Annual heating requirements (GJ) and CO_2 emissions (tonnes) from gas and reverse cycle air-conditioning to heat a house with floor area of 160 m^2 and insulated ceiling (ACS, 1999). Average firewood burned, from BDA (2006). 1 tonne of firewood contains about 16 GJ energy, so assuming 60% average efficiency (typical AS4013 laboratory test results), about 9.6 GJ is delivered to the living area. Usage efficiency is the ratio of heat needed for the living area (40% of the central heating total) to the amount delivered to the living area.

(A): CO_2-equivalent from methane calculated as 468 kg per tonne of firewood (see text, Section 2.2, and Table 1).

(B): CO_2 emissions = 2 tonnes per tonne of firewood (Gras, 2002).

(C): CO_2 emissions for supplementary heating of other rooms calculated as 20% of the estimate by ACS (1999) for radiant electric heating for a 160 m^2 house.
[a] *The weighted average was intended to show the effect of replacing an average wood heater by alternatives, so the weights are the estimated percentages of total particle emissions (Brisbane 0.9%, Perth 23.3%, Sydney 47.0%, Melbourne 22.3%, Canberra 6.5%, Table 3) which should be proportional to the amount of firewood burned in each city.*

3.2. Non–centrally heated houses – CO_2 emissions

Although some wood heaters can be used as part of a ducted central heating system, most are stand–alone units that heat only the living area. A generous sized living area might be about 10 m x 6 m, slightly less than 40% of the floor area of a 160 m^2 house. In a non–centrally heated house, the remaining 60% will not be heated all the time. A plausible assumption is that the living area will need 40% of the energy required for centrally heating a 160 m^2 house, and that the remaining 60% of the house will use electric radiant heating when needed, consuming only 20% of the energy required for centrally heating a 160 m^2 house.

The values in column (C) of Table 2 were therefore calculated as 20% of the ACS (1999) estimates of CO_2 emissions for heating a 160 m^2 house with electric radiant heating. Assuming the living area uses 40% of the energy needed to centrally heat the entire house, the averages of 1.3 tonnes of CO_2 for gas and 1.6 tonnes for rcAC (Table 2) imply emissions of 0.53 and 0.65 tonnes for just the living area. Household totals including supplementary heating (1.1 tonnes, Table 2) are therefore 1.6 and 1.8 tonnes of CO_2. A gas or rcAC system for the living area and supplementary electric radiant heating elsewhere will therefore have slightly higher greenhouse gas emissions (and running costs), offsetting the lower installation costs.

3.3. Wood heating – CH_4 and CO emissions

Methane emissions from wood heating in the living area in Brisbane, Perth and Sydney (respectively 0.5, 1.2 and 0.9 tonnes of CO_2–eq per year, Table 2) are similar to or greater than heating an entire 160 m^2 house with gas (0.3, 0.5 and 0.9 tonnes). In Melbourne and Canberra, the methane from heating the living area with wood produces less CO_2–eq than central heating, but after accounting for supplementary heating in other rooms, the total global warming effect is greater than gas central heating.

The above calculations are based on the 100–year GWP from AR4. Table 1 shows that the true effect could be much worse. If the latest NASA estimates for CH_4 and CO are closer to the true warming potentials, or there is a chance a tipping point will be reached in less than 100 years, domestic wood heating, even with sustainably sourced firewood, could cause as much global warming as heating 5 similar houses with gas.

Although these results apply to Australian wood heating, similar concerns are likely to apply in other countries. In the US, in–service emission from USEPA Phase II woodstoves averaged 9.7 g/kg (Fisher et al., 2000), only marginally less than the 12.5 g/kg used here as the best estimate for Australian wood heaters. Rector et al. (2006) reported that most US outdoor wood boilers (OWB) have operating efficiencies in the range of 30–40%, that in field testing, the internal stack temperature "never reached levels that would have resulted in complete combustion" and average fine particulate emissions from the OWB tested were "equivalent to the emissions from 22 EPA certified wood stoves, 205 oil furnaces, or as many as 8 000 natural gas furnaces". A follow–up study reported particle emissions from non–catalyst OWB ranged from 24 to 265 g/hr (NESCAUM, 2008), indicating that methane emissions would also be very high.

3.4. Global warming – non sustainably–sourced wood

The last column of Table 2 includes the CO_2 emissions from wood heating. Domestic wood heaters became popular in Australia because of abundant supplies of cheap firewood from non–renewable sources such as land clearing and tree dieback. These supplies are drying up, with firewood cutters forced to travel increasingly long distances to collect wood. A study of one area showed that current firewood use is not ecologically sustainable (MacNally et al., 2000) and another reported that 80–90% of Canberra's firewood supply is sourced from dead standing paddock trees up to 400 km away (McArthur, 2010). It could be argued that the depletion of this non–renewable resource is equivalent to the depletion of fossil fuel reserves. If the CO_2 from burning the wood is included, weighted average emissions are 7.7 tonnes of CO_2–eq (A+B+C, Table 2), almost six times the weighted average emissions for gas (1.3 tonnes) or five times the average for rcAC (1.6 tonnes).

3.5. Limited sustainable supply

Although re–growth of sustainably harvested eucalypts could offset CO_2 emissions (but not the CH_4 that causes as much global warming as heating the same rooms with gas), there is some controversy surrounding the definition of sustainable harvesting for native forests. In the Murray–Darling Basin, 71% of native forests have been cleared (West et al., 2008a), and it has been argued that firewood harvesting in the remaining 29% should be considered sustainable only if there is no additional threat to wildlife. New measures to protect the area include the creation of two National Parks totaling more than 200 000 ha (NPA, 2010) that will reduce commercial firewood harvesting by about 80 000 tonnes per year.

One species considered vulnerable because of loss and degradation of habitat, is the superb parrot (estimated population 6 500). Although Chester (2009) suggested that it might be possible to protect the superb parrot and continue logging, West et al. (2008a) argued that biodiversity could suffer if average woody debris in the Murray River Basin declined substantially from the norm of 20 t/ha expected in the absence of firewood collection.

An alternative of harvesting live trees was suggested, but this would barely be able to satisfy the area's existing firewood demand (West et al., 2008a). Plantations are another possibility. In the Murray Darling Basin, estimates of minimum plantations sizes to supply 2.25 M tonnes of firewood per year range from 200 000 to 600 000 ha, depending on rainfall. Due to the practicalities of plantation establishment, West et al. (2008b) noted that appreciably larger areas than these minima would be required. Plantations were also suggested as a possible solution for the Northern Tablelands; the estimated land area was 1 ha for every wood heater in use (Curtis, 2001).

Currently, plantation timber is Australia's 4th major crop by land area, occupying 1.9 million ha (wheat occupies 12.3 million, horticulture 5.7 million and barley 4.2 million ha; DAFF, 2009). With an estimated 8.5 million households in Australia (ABS, 2004) even if only 25% use wood heating, hardwood plantations of up to 2 million ha would be required – more than the entire Australian land area currently devoted to plantations. This demonstrates that there is only a limited supply of sustainably–produced eucalypt firewood.

Softwood plantations are not a viable alternative because of the increase in methane and particulate emissions from burning softwood in Australian wood heaters. Gras (2002) reported average methane emissions of 30 g/kg (i.e. 750 g CO_2–eq/kg) for pine. In Gras' study, laboratory tests on hardwood (mostly correctly–operated heaters) had much lower particle emissions (4.5 g/kg) than the 9.4 g/kg average for AS4013 heaters under normal householder operation. The laboratory test average of 30 g CH_4 per kg softwood is also likely to underestimate emissions from normal householder operation. Yet even with this conservative estimate, Table 2 shows that burning softwoods in Australian wood heaters would result in more global warming than the other forms of heating. These results are consistent with the warning (Johansson et al., 2004) that methane emissions from an old–type Swedish wood boiler "may have more than twice as high an impact on climate change as an oil boiler."

3.6. Better uses for sustainably–produced wood

Given the limited supply, it is relevant to follow the example of Gustavsson et al. (2007) and ask what is the most effective use of sustainably–produced timber – would there be greater reductions in Australia's total greenhouse gas emissions from using the wood for other purposes than firewood? Possible competing uses include partial replacement of coal in power stations (co–firing), local small–scale uses such as combined heat and power plants, pellets for wood pellet heaters, as well as potential new uses such as producing ethanol to replace petrol.

Co–firing. A US lifecycle assessment of co–firing concluded that replacing 5% and 15% (by heat input) of coal with biomass reduces CO_2–eq emissions by 5.4% and 18.2%, and also reduces SO_2, NO_x, non–methane hydrocarbons, particulates, CO and solid waste generation (Mann and Spath, 2001). This, however, was based on the assumption that the wood would otherwise be wasted, an increasingly untenable assumption if universal carbon trading schemes are introduced.

Co–firing is feasible for all types of coal–fired power stations (De and Assadi, 2009). Little or no modification is required for 5% wood mixed with coal (Tillman, 2000). In pulverized coal boilers, mixes with more than 5% wood may require the wood to be pulverized separately before either blending with coal or injecting into the boiler via a separate port – this is still considered a relatively low cost option (Tillman, 2000). Allowing for a small loss of boiler efficiency ($EL = 0.0044B^2 + 0.0055B$, where B is the percentage by weight of biomass), burning of a mix with 5% of energy from wood would therefore save 0.97 MJ of coal energy for every MJ of replacement wood energy. Coal emits 0.1 kg CO_2 per MJ (CCSD, 2009) so that burning 1 kg of wood (16 MJ) saves 0.97 x 16 = 15.48 MJ of coal burning and the associated emission of 1.548 kg of CO_2.

Thus if the 4.5 to 5 million tonnes of firewood currently burned in domestic wood heaters were instead used to replace coal in power stations in a 5% blend, it would avoid emission of about 7.35 million tones of CO_2 from coal, plus 2.22 million tonnes CO_2–eq as methane emissions from wood heaters (using the lowest estimate in Table 1 of 468 g of CO_2–eq per kg firewood), with estimates up to 12 times higher depending on the time horizon, the model used to calculate GWP and whether warming from CO is included.

Offsetting this are the additional CO_2 emissions from replacement heating. An additional 0.53 tonnes of CO_2 (40% of 1.3 tonnes, see Section 3.2) will be emitted if the replacement is gas heating for the living area (no change to supplementary heating), or 0.65 tonnes for rcAC. Central heating (average 1.3 tonnes CO_2 for gas, 1.6 for rcAC, Table 2) replaces main and supplementary heating (average 1.1 tonnes CO_2), so the net change is 0.2 to 0.5 tonnes CO_2. Rounding up the mean of these 4 values (0.65, 0.53, 0.2, 0.5) leads to an estimated 0.5 additional tonnes of CO_2 per year for the average Australian household.

With average firewood consumption of 2.7 tonnes per household (Table 2), 4.75 million tonnes will supply 1.76 million households, generating 1.76 x 0.5 = 0.88 million tones of CO_2 emissions from replacement heating, much less if home insulation is improved as part of the replacement package, or newer, highly efficient rcAC models are used. One model listed on the Australian Government's energy rating website (www.energyrating.gov.au) uses just 0.45 kW of electricity when the external ambient temperature is 2 °C to produce 3.54 kW of heat, 7.9 times the electric energy used. A minimal impact on electricity consumption was demonstrated in NZ by Christchurch's Clean Heat Project, where the increase in electricity use for the 1 973 households that replaced wood heaters with rcAC (and improved insulation, if needed) was just 1% (O'Connell et al., 2010).

Thus using the limited sustainable supplies of firewood to replace coal in power stations reduces CO_2 emissions from coal by 7.35 million tonnes, CH_4 from wood heaters by 2.2 million tonnes CO_2–eq, offset by up to 0.88 million tones of CO_2 from replacement heating, a net reduction of 8.7 million tonnes (or substantially more, depending on the time horizon, choice of GWP, whether the warming from CO is included, and whether insulation is upgraded at the same time as replacing the wood heater). To put this in perspective, passenger cars were responsible for 41.9 million tonnes of CO_2–eq in 2007 (DCC, 2009) so a reduction of 8.7 million tonnes is equivalent to taking about 21% of Australia's passenger cars off the road. Alternatively, a domestic 1 kW rooftop photovoltaic system generates about 1 500 kWh of electricity per year, saving about 1.5 tonnes of CO_2 emissions, i.e. about 5.8 million domestic 1 kW rooftop systems are needed for a saving of 8.7 million tonnes.

Smaller–scale uses. Smaller–scale uses such as local combined heat and power (CHP) units could potentially result in even greater reductions in greenhouse emissions. As long as the appliances burn efficiently with no methane emissions, households could have heating, hot water and a substantial proportion of their electricity for similar fuel consumption to that required for remotely–generated electricity. Wood gasification is a promising technology that could ensure installations are efficient and have very low emissions of health–hazardous particle pollution.

Wood pellet heaters are another way of achieving relatively efficient burning (and hence low CH_4 emissions) that can be controlled according to the heating needs of the household. Although particulate pollution emissions (about 0.5 to 1 g/kg) are still undesirably high, many models have electronic control, allowing programmable start and stop times and thermostatic temperature control. This reduces fuel consumption – householders don't waste energy by heating an empty (and often poorly insulated) living area when they are in bed or when the house is unoccupied during the day, and there is no need to open windows to cool the house when the living area is uncomfortably hot, yet the wood heater continues to belch out about 4 kW of unwanted heat (Atech, 2001).

These facts suggest that, if heaters could be turned off when the heat is not needed, many more homes could be heated for the same amount of fuel, leading to substantial reductions in total greenhouse gas emissions. Table 2 shows that the average wood heater in the living area burns about 2.7 tonnes of firewood producing 26 GJ heat. Based on estimated heating needs of 7.04 GJ (40% of the 17.6 GJ requirement of a 160 m^2 house), average efficiency of use is 26% (Table 2). An 85% efficient pellet heater would require just 0.44 tonnes of pellets (18.77 GJ/tonne) to supply 7.04 GJ of heat.

Domestic log heaters will not achieve the same reductions in greenhouse gas emissions unless new models are developed with minimal methane and particulate emissions, in conjunction with cost–effective ways to either control heat output or store unwanted heat (e.g. water tanks; Johansson et al., 2004). Currently about half of all Australian wood heaters are used overnight (Todd, 2008), partly to avoid the bother of re–lighting in the morning. Except for poorly insulated houses in colder areas, where retrofitting insulation would be a better long–term option, conventional Australian domestic log heaters without heat storage will continue to cause more global warming than using the wood for other purposes.

Perhaps the best solution for future heating would be to develop solar air heating, which could halve heating needs, providing clean, free heat from the sun for less than the cost of installing a wood heater (Solar Project, 2001).

3.7. Black carbon

Shindell and Faluvegi (2009) suggest that there are two types of aerosols. Sulfate aerosols scatter incoming solar radiation and have a net cooling effect. In contrast, aerosols containing black carbon – small, soot–like particles from industrial processes and the combustion of biofuels and diesel – absorb incoming solar radiation and have a strong warming influence on the atmosphere. The radiative forcing of current black carbon levels is estimated at +0.9 W/m^2, more than half the value of current CO_2 forcing (Arneth et al., 2009).

Although forest burn–offs are a major source of black carbon emissions in rural Australia, domestic wood heaters are the largest single source in most Australian cities. In Sydney, for example, despite the fact that only 4.3% of households use wood heaters as the main source of heating for the living area (with occasional use by a further 2.2%; Todd and Solomon, 2009), they are the largest single source of $PM_{2.5}$ pollution (4 503 tonnes, 34.3%), the next largest next being industrial off–road vehicles and equipment (1 152 tonnes, 8.8%) with exhaust emissions from light diesel vehicles (840 tonnes, 6.4%) third (NSWDECC, 2007). Although beyond the scope of this paper, future evaluations might consider the effect of black carbon in the smoke from domestic wood heating on global warming.

3.8. Increased global warming from activity of people affected by smoke

Greenhouse gas emissions can also be increased by activities needed to avoid or mitigate the health consequences of air pollution from domestic wood heaters. For example, in Armidale, NSW (population 22 000), where about half of households use wood heaters, Khan et al. (2007) estimated that wood–smoke causes 8.8 additional visits to GPs for respiratory complaints per day, i.e. about 750 additional visits per winter, increasing the need for travel to see doctors and pick up medicines at pharmacies. Using measured pollution levels and international dose–response rates, Robinson et al. (2007) estimated that 115 life–years were lost annually because of exposure to wood–smoke. Valuing a healthy year of life at AU$130 000, this equates to a health cost of AU$4 270 for every wood heater in the city. In fact, a local doctor advised people with respiratory complaints to move out of Armidale (Fuller, 2008). Living on rural blocks out of town may be a good strategy to avoid the health effects of air pollution, but it generates longer journeys to work, and so increases greenhouse gas emissions from car travel. Families affected by wood–smoke may also need to use electric air filters and electric clothes driers, also increasing total greenhouse gas emissions.

3.9. Health costs

As awareness of the potential health problems increases, wood–smoke avoidance activities are also likely to increase, perhaps until the cost of avoidance is comparable with the perceived benefits of avoiding smoke.

It is therefore relevant to consider health costs, to indicate the potential for increased greenhouse emissions if more people choose to avoid breathing wood–smoke. BDA (2006) reviewed the literature on health costs (morbidity and mortality) per kg of PM_{10} emissions, reporting a range of values from $134 for Sydney and $128 for Melbourne (the two most densely populated cities) to $80 for Perth and $43 for Brisbane and South East Queensland. Table 3 provides estimates of the average emissions per heater per year (multiplying average wood use by the emission factor of 12.5 g $PM_{2.5}$ per kg firewood). Average health costs were calculated by multiplying the health costs of emissions in each city by average emissions per heater (kg $PM_{2.5}$, equal to PM_{10} emissions because, as noted by Larson and Koenig (1994), virtually all wood–smoke particles are less than 1 micron). The estimates range from $593 in Brisbane to $6 897 per heater per year in Melbourne (Table 3).

Although these costs seem relatively high, Fisher et al. (2007) showed that in Christchurch, NZ, (after adjusting for other factors such as age, sex, ethnicity, socio–economic status and tobacco smoking habits), death rates increased with wood–smoke levels. Estimates for each increase of 10 μg/m^3 of PM_{10} exposure were: 34% more respiratory deaths, 11% more circulatory deaths and 8% more deaths overall. This implies that living in the most polluted areas (>20 μg/m^3 PM_{10}) increases mortality by about 16% (respiratory deaths by about 68%) compared to living in unpolluted areas with <1 μg/m^3. Estimates of health costs from an earlier study assuming only 4.3% increased mortality per 10 μg/m^3 PM_{10}, were approximately NZ$2 700 per heater per year. The observed increase in death rates was 8%; thus the true health costs are likely to exceed NZ$4 000 per heater per year.

Although other pollutants, e.g. PAH, can cause serious health problems (Solli et al., 2009), estimates of the health costs of fine particle pollution necessarily include the health effects of PAH and other chemicals that adhere to them. In area affected by wood–smoke $PM_{2.5}$ and PAH levels are highly correlated. Indeed, in Canberra, two thirds of all PM_{10} and two thirds of all PAH are emitted by wood heaters (NPI, 2009), used as the main source of energy for space heating by only 3.9% of households.

Table 3. *Estimated health costs per wood heater per year*

	Emissions tonnes PM [a]	% of total	wood use tones/heater [b]	kg PM/heater.year	health costs per kg PM [b]	Annual health costs per heater
Brisbane/SEQ	89	0.9%	1.1	13.8	$43.11	$593
Perth	2 300	23.3%	2.5	31.3	$80.21	$2 507
Sydney	4 642	47.0%	1.9	23.8	$133.54	$3 172
Melbourne	2 200	22.3%	4.3	53.8	$128.31	$6 897
Canberra	640	6.5%	3.7	46.3	$81.85	$3 785
Wted ave [c]			2.7	33.6	$115.78	$3 863

[a] *PM_{10} emissions for SE Qld, Perth, Port Phillip (Melbourne) and Canberra airsheds from the 2008/09 National Pollutant Inventory (www.npi.gov.au). The NPI aggregates emissions for the entire metropolitan region of Sydney, Newcastle and Wollongong, so Sydney PM_{10} emissions are from Table ES9, NSWDECC (2007).*

[b] *Wood use from and health cost per kg PM emissions from BDA (2006); PM emissions (kg per heater per year) calculated assuming 12.5 kg PM (see text) per tonne of firewood.*

[c] *Weighted by column 3 of this table (PM emissions from each city as percent of the total for all 5 cities).*

Increasing awareness of health costs could be a driving force for developing non–polluting alternatives such as solar heating, or switching to more efficient uses such as pellet heaters or local wood–fired CHP, which will also reduce methane emissions and consequently global warming.

4. Conclusions

Claims that wood heating is greenhouse neutral are incorrect. Table 2 shows that global warming from methane emissions of a wood heater in the living room (weighted average 1.3 tonnes of CO_2–eq) are similar to the CO_2 emissions from heating an entire 160 m^2 house with gas. When emissions from supplementary heating are considered, wood heating appears to be the worst option, even if all the wood is from a sustainable source. Indeed, depending on the time horizon, the sustainability of the firewood supply, whether GWP from AR4 or Shindell et al. (2009) are used, and whether warming from CO is included, wood heating could be considered to cause more than 10 times as much global warming as gas or reverse cycle air–conditioning.

Thus, except for models with minimal methane and particle emissions and effective ways of storing any unwanted heat, domestic wood log heaters should not be advertised as greenhouse neutral. A better option is to develop and promote cleaner environmentally friendly methods such as solar heating, along with more efficient uses of sustainably–produced wood, e.g. local wood–fired CHP installations, wood pellet heaters, or replacing coal in power stations with sustainably–produced biomass.

Acknowledgement

The contribution of Prof. John Todd in providing the methane emissions data and the equation relating methane and particle emissions is gratefully acknowledged.

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