Australian wood heating can increase global warming

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Abstract

A study published in 2006 concluded that firewood production can be CO_2-neutral, if the carbon dioxide emitted by burning the wood is absorbed by replacement trees. However, burning firewood in domestic heaters produces methane and black carbon particles that increase global warming. Methane from the average wood heater in Brisbane, Perth or Sydney is estimated to cause at least as much global warming as heating an entire 160 square metre house with gas. 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 electric heating.

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 electric heating. 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

1 Introduction

Policymakers are interested in the contribution of home heating to greenhouse gas emissions.[1] Firewood harvested from a continually renewed supply has the potential to be CO_2-neutral.[1] This is often incorrectly interpreted as meaning that wood heating emits less greenhouse gases than other forms of heating.[2] In fact, the current generation of wood heaters in Australia emit substantial quantities of methane, which causes 25 times as much global warming as the same amount of CO_2 over a 100 year horizon (and 72 times as much over 20 years).[3] The total effect on global warming of wood heaters in Australia is estimated, to facilitate comparison with other forms of heating and other uses of biomass.

2 Methods

Published literature was reviewed to obtain estimates by location of Australian firewood consumption, wood heater emissions, and also energy use and greenhouse gas emissions for flued gas and reverse cycle electric heating.

2.1 Wood heater emissions – laboratory tests

A comprehensive laboratory study measured emissions from 4 Australian wood heaters (two freestanding models satisfying the Australian Standard AS4013, a fireplace insert satisfying AS4013 and a popular well-used heater made in 1985) for a range of fuels and burn rates.[4] 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 pine, for which particle emissions ranged from 7 to 29.4 (mean 15.8) g/kg.

Combustion efficiency (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 firewood burned, 1.9 for pine), carbon monoxide (CO, average 120 g per kg for eucalypt, 220 for pine), methane, acetic acid, formaldehyde, benzene and unspecified Volatile Organic Compounds (VOC). There was a consistent relationship between particle emissions and combustion efficiency.[4]

Data from the above study[4] (shown in Fig 1) was used by a consultant, John Todd, (Todd, personal communication) to derive the equation used by the Australian Department of Climate Change to calculate methane emissions from wood heaters burning eucalypts[5]:

$$CH_4\ (g\ kg^{-1}) = 1.495 \times \text{particle emissions}\ (g\ kg^{-1}) \quad \text{(Equ 1).}$$

A different equation is needed for softwoods, with CH_4 ($g\ kg^{-1}$) equal to about 2.15 times particle emissions ($g\ kg^{-1}$, see Figure 1).

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. Consequently, residential emissions are much higher. A New Zealand study measured emissions from 5 heaters (average AS4013 rating of 1.0 g/kg) installed in people's homes. Residential emissions averaged 15 g/kg, 15 times the AS4013 average.[6]

Real-life emissions were also measured for 18 AS4013 heaters in Launceston, Tasmania, where education programs, including a $2 million federally-funded woodsmoke reduction program, had alerted the public to the serious health problems caused by breathing woodsmoke, with 70% of wood heater users switching to non-polluting heating.[7, 8] Knowing the health effects of woodsmoke and that their emissions were being measured, the volunteers would have been motivated to take the time and trouble to operate their heaters correctly. Indeed, there was no evidence heaters were "*allowed to smoulder overnight; in contrast they appeared to be refuelled 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,[8] more than twice the limit specified for the AS4013 laboratory test, twice the average in the comprehensive laboratory study,[4] and almost twice the emissions factor (5.5 g/kg) in the National Pollutant Inventory (NPI). 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 woodsmoke, so in-service emissions would be substantially higher than Launceston.[9]

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*12.5 = 18.7 grams of methane per kg firewood. With an estimated 4.5 to 5 million tonnes of firewood burned in Australia, estimated CH_4 emissions are 88,800 tonnes, twice the 43,780 tonnes reported in the 2007 Australian National Greenhouse Inventory for CH_4 from residential biomass burning,[10] consistent with the new information from the real-life emissions study (published 2008)[8] that measured in-service emissions are much higher than NPI estimates.

2.3 GWP of non-CO_2 greenhouse gases

Table 1 summarises estimates of global warming potential (GWP) for methane and CO from the IPCC Fourth Assessment Report (AR4), and also by researchers at NASA (published October 2009), who modelled interactions of gases and aerosols and concluded that the effect of methane on global warming has been under-estimated.[11] Moreover, with current levels of radiative forcing (RF) approaching levels historically correlated with an ice-free planet, a tipping point could be reached in less than 100 years.[12] 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, if a tipping point could be reached in less than 100 years, or if the effect of CO (noted in the real-life emissions study to account for about 15% of fuel carbon[8], 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

3.4 CO_2 emissions - central heating

Estimates of the energy required to heat a 160 square metre house (with insulated ceiling) in Australian Capital cities are shown in Table 2. The values (from Choice Magazine [13]) range from 4 GigaJoules (GJ) per year in Brisbane to 40 GJ in Canberra (Table 2).

The accompanying notes explain that energy requirements were calculated from climate information, assuming that heating is used for a short period of time in Brisbane and increasing longer periods in other cities according to the climate. Consequently, 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) and let 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.[14] 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, far more than the 3.6 to 12.3 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 houses are heated for longer periods of the day, reducing the amount of energy wasted by an appliance that produces large quantities of heat (normally at least 4 kW on the lowest setting) for 6 or more hours. Nonetheless, substantial inefficiencies remain. Even in 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. Note also that 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 electric heating.[13] Some households might therefore economise by lighting the wood heater only on relatively cold days when substantial heat is needed for long periods. 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 consequently under-estimate greenhouse emissions in these circumstances.

3.5 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 require 40% of the energy needed to heat 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 CO_2 emissions for heating a 160 m^2 house with electric radiant heating.[13] Based on the assumption that the living area requires 40% of the energy needed to centrally heat the entire house, the averages of 1.8 and 2.3 tonnes for gas and reverse cycle electric heating for the entire house (Table 2) imply heat requirements of 0.71 and 0.93 tonnes for just the living area. Household totals including supplementary heating (1.6 tonnes, Table 2) are therefore 2.3 and 2.5 tonnes of CO_2. A gas or reverse cycle system for just 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.

3.6 Wood heating – CH_4 and CO emissions

Methane emissions from wood heating 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 will be greater than gas central heating.

The above is 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, burning wood, even from a sustainable source, could cause as much global warming as heating 5 similar houses with gas.

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 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 well below ecologically sustainable levels.[15] It could therefore be argued that the depletion of this resource is equivalent to the depletion of fossil fuel reserves. If the CO_2 from burning the wood is included, weighted average emissions are about 10 tonnes of CO_2-eq (A+B+C, Table 2), more than five times weighted average emissions for gas (1.8 tonnes) or four times the average (2.3 tonnes) for reverse cycle electric heating.

3.7 Limited sustainable supply

Although regrowth of sustainably harvested eucalypts has the potential to offset CO_2 emissions (but not CH_4 which still causes almost as much global warming as gas or reverse cycle electric heating), there is some controversy surrounding the definition of sustainable harvesting for native forests. Australia's Superb Parrot (estimated population 6,500), for example, is considered vulnerable, because land clearing has resulted in loss and degradation of habitat.[16] With native forests cleared from nearly 71% of the Murray-Darling Basin,[17] it could be argued that firewood harvesting in the remaining 29% of native forests should be considered sustainable only if there is no additional threat to wildlife. Although it might be possible to protect the superb parrot and continue logging,[18] the authors of one study argued that biodiversity would suffer if average woody debris in the Murray River Basin declines from the norm of 20 t/ha expected in the absence of firewood collection.[17]

An alternative of harvesting live trees was suggested, but this would barely be able to satisfy the area's existing firewood demand.[19] Plantations are another possibility. In the Murray Darling Basin, minimum plantations sizes to supply 2.25 M tonnes of firewood per year range from 200,000 to 600,000 ha, depending on rainfall. However, the study authors noted that, due to the practicalities of plantation establishment, appreciably larger areas than these minima would be required.[19] Plantations have also been suggested as a possible solution for the Northern Tablelands; the estimated land area was 1 ha for every wood heater in use.[20]

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[21]). With an estimated 8.5 million households in Australia 2010,[22] even if only 25% use woodheating, hardwood plantations of up to 2 million ha would be required – more than the entire Australian land area currently devoted to plantations. This implies there will be limitations to the 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.[4] A similar problem was highlighted by a Swedish study comparing older heaters with efficient-burning modern downdraft heaters that had long flame paths and water storage tanks.[23] The worst case was an updraft batch-loaded model with particulate emissions similar to those observed from the low burn cycle of simulated real-life tests of Australian heaters.[23, 24] Readers were warned that methane emissions from an old-type wood boiler "*may have more than twice as high an impact on climate change as an oil boiler*".[23]

3.8 Better uses for sustainably-produced wood

Given the limited supply, it is relevant to ask if firewood is the most effective use of sustainably-produced timber, or if there would be greater reductions in Australia's total greenhouse gas emissions by using the wood for other purposes?

Possible competing uses for biomass include partial replacement of coal in power stations (co-firing) and local small-scale uses such as combined heat and power plants or pellets for wood pellet heaters, as well as potential new uses such as producing ethanol to replace petrol.

3.8.1 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, NOx, non-methane hydrocarbons, particulates, CO and solid waste generation.[25] 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.[26] Little or no modification is required for 5% wood mixed with coal.[27] In pulverised coal boilers, mixes with more than 5% wood may require the wood to be pulverised separately before either blending with coal or injecting into the boiler via a separate port – this is still considered a relatively low cost option.[27] Allowing for a small loss of boiler efficiency ($EL = 0.0044B^2 + 0.0055B$, where B is the percentage by weight of biomass),[27] 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,[28] so that burning 1 kg of wood (16 MJ) saves 0.97 x 16 = 15.48 MJ of heat from burning coal 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 tonnes 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 $C0_2$ emissions from replacement heating. If the replacement heats only the living area (no change to supplementary heating), expected increases are 0.71 tonnes (gas) or 0.93 tonnes (reverse cycle heat pump, see Section 3.5). If a wood heater is replaced by gas central heating (average 1.8 tonnes, Table 2), there will be no need for supplementary heating (average 1.6 tonnes) so the net change is 0.2 tonnes. For reverse cycle central heating the average net change is 2.3 – 1.6 = 0.7 tonnes (Table 2). These averages mask the fact that gas and reverse cycle heating have very similar emissions except in Victoria, where carbon trading schemes could disproportionately affect the cost of electricity, so that households are more likely to switch from wood to gas. The average net increase in CO_2 for replacement heating was therefore assumed to be 0.6 tonnes per household per year.

With average firewood consumption of 3.2 tonnes per household (Table 2), 4.75 million tonnes will supply 1.47 million households, generating 1.47 x 0.6 = 0.88 million tonnes of CO_2 emissions from replacement heating. Thus the reduction in CO_2-eq from using the limited sustainable supplies of firewood to replace for coal in power stations reduces CO_2 emissions from coal by 7.35 million tonnes, CH_4 from woodheaters by 2.2 million tonnes CO_2-eq, offset by 0.88 million tonnes 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, and whether the warming from CO is included). To put this in perspective, passenger cars were responsible for 41.9 million tonnes of CO_2-eq in 2007,[29] 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 1500 kWh of electricity per year, saving about 1.5 tonnes of CO_2 emissions, so about 5.8 million domestic 1 kW rooftop systems are needed for a saving of 8.7 million tonnes.

3.8.2 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 increases efficiency. Pellet Fires Tasmania, for example, claim that "*One tonne of pellets equates to around 4 - 5 tonnes of firewood.*"[30]

Thus many more homes could be heated for the same amount of fuel, if heaters can be turned off when a comfortable temperature has been reached, substantially reducing total greenhouse gas emissions, compared with inefficient use in methane-producing domestic log-burning heaters.

This implies that, even if new clean-burning log heater with minimal methane emissions could be developed, because of inefficiency of use, the same amount of fuel used in other forms of heating (pellet heaters, CHP, wood gasifiers) could supply many more houses and so produce much greater reductions in total Australian greenhouse emissions. Unless cost-effective ways can be found of controlling heat output, or as in other countries using water tanks or other devices to store the heat when not required,[23] log heaters will be suitable only for uninsulated houses in colder areas, with retrofitting insulation a much better long-term option.

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.[31]

3.9 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, people with respiratory complaints were advised to move out of Armidale, NSW, a city where about half of households use wood heating, leading to high and unhealthy pollution levels.[32] 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. In Armidale (population 22,000) woodsmoke is estimated to cause 8.8 additional visits to GPs for respiratory complaints per day,[33] i.e. about 750 additional visits per winter, increasing the need for travel to see doctors and pick up medicines at pharmacies. Families affected by woodsmoke may also use electric air filters, and electric clothes driers, also increasing total greenhouse gas emissions.

3.10 Black carbon

New research (published 2009) shows there are two types of aerosols. Sulphate 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 [34]. The radiative forcing of current black carbon levels is estimated at +0.9

W m^{-2}, more than more than half the value of the current CO_2 forcing.[35]

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%)[9], they are the largest single source of PM2.5 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.[36]

3.11 Health costs

As noted earlier, awareness of the potential health problems from breathing woodsmoke encourages people to live out of town and drive longer distances, or use other measures such as electric air filters to avoid the health consequences of woodsmoke. As awareness increases, woodsmoke avoidance activities will increase, perhaps until the cost of avoidance is comparable with the perceived benefits of avoiding smoke.

It is therefore relevant to consider health costs, and the potential for increased greenhouse emissions if more people choose to avoid breathing woodsmoke. Table 3 provides estimates of the health costs per wood heater per year, derived from estimates of the health costs per tonne of PM10 used in an economic analysis of woodheater emissions by BDA Group.[14] The BDA analysis was published before the study of real-life emissions in Launceston[8], so under-estimates average particle emissions from AS4013 heaters, which, as discussed in Section 2.2 are now thought to average 12.5 g/kg. Estimated health costs based on average emissions of 12.5 g/kg range from $593 in Brisbane to $6,897 per heater per year in Melbourne (Table 3).

Although these costs seem relatively high, analyses published in 2007 of woodsmoke in Christchurch, NZ, show that (after adjusting for other factors such as age, sex, ethnicity, socio-economic status and tobacco smoking habits), death rates increased with smoke levels. Estimates for each increase of 10 $\mu g/m^3$ of PM10 exposure were: 34% more respiratory deaths, 11% more circulatory deaths and 8% more deaths overall.[37] This implies that living in the most polluted areas (>20 $\mu g/m^3$ PM10) increases mortality by about 16% (respiratory deaths by about 68%) compared to living in unpolluted areas with <1 $\mu g/m^3$. Estimates of health costs from an earlier study assuming only 4.3% increased mortality per 10 $\mu g/m^3$

PM10, 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.

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 1.5 tonnes of CO_2-eq) are similar to or greater than 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, whether warming from CO is included, whether GWP from AR4 or Shindell et al. are used (Table 1), and the sustainability of the firewood supply, wood heating could be considered to cause more than 10 times as much global warming as gas or reverse cycle electric heating.

Domestic wood heaters should not be advertised as greenhouse neutral. Instead, cleaner environmentally friendly methods such as solar heating should be developed and promoted, 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.

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6 References

1. Paul, K., et al., *Net carbon dioxide emissions from alternative firewood-production systems in Australia.* Biomass and Bioenergy, 2006. **30**(7): p. 638-647.
2. Hamilton, L., *Firewood and Woody Biomass and their Role in Greenhouse Gas Reduction, Agriculture Notes*. 2008, Department of Primary Industries, Victoria: Colac.
3. Forster, P., et al., *Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.* 2007.
4. Gras, J., *Emissions from Domestic Solid Fuel Burning Appliances.* 2002, Environment Australia Technical Report No. 5, March 2002.
5. DCC, *Australia's national greenhouse accounts, National Inventory Report 2007 Volume 1*. 2009, Department of Climate Change, Commonwealth of Australia. (Available at: http://www.climatechange.gov.au/~/media/publications/greenhouse-acctg/national-inventory-report-vol-1-part-a.ashx The methodology used to calculate methane emissions from woodheaters is on page 64, headed Residential - Biomass Combustion (1.A4)).
6. Scott, A.J., *Real-life emissions from residential wood burning appliances in New Zealand*. 2005, Environment Canterbury, August 2005.
7. DEH & CSIRO, *Woodheaters in Launceston – Impacts on Air Quality*. 2005, CSIRO Atmospheric Research, Aspendale Victoria 3195.
8. Meyer, C.P., et al., *Measurement of real-world PM10 emission factors and emission profiles from woodheaters by in situ source monitoring and atmospheric verification methods*. 2008, CSIRO Marine and Atmospheric Research (CMAR), (available at: http://www.environment.gov.au/atmosphere/airquality/publications/emission-factor.html).
9. Todd, J. and T. Solomon, *Woodsmoke Reduction Workshop Notes*. 2009, NSW Department of Environment and Climate Change, Sydney.
10. DCC, *Australian Greenhouse Emissions Information System (AGEIS)*. 2010, Australian Government Department of Climate Change (available at: http://ageis.climatechange.gov.au/ Emissions from domestic woodheaters are categorised as: Energy - Fuel Combustion - Other Sectors - Residential - Other; Gas - Methane, All Fuel - Renewable).
11. Shindell, D.T., et al., *Improved Attribution of Climate Forcing to Emissions.* Science, 2009. **326**(5953): p. 716-718.
12. Jackson, S.C., *Parallel Pursuit of Near-Term and Long-Term Climate Mitigation.* Science, 2009. **326**(5952): p. 526-527.
13. Choice Magazine, *Your heating options, April*. 1999.
14. BDA Group, *Wood heater Particle Emissions and Operating Efficiency Standards: Cost Benefit Analysis*. 2006, Report prepared for the Department of the Environment and Heritage (Available

at: http://www.environment.gov.au/atmosphere/airquality/publications/pubs/wood-particle-emissions.pdf).

15. MacNally, R., et al., *Ecological significance of coarse woody debris on south-eastern Australian floodplains. Report Number R7007. Murray-Darling Basin Commission, Natural Resource Management Scheme I & E Program, Riverine Program.* 2000.
16. Wilkinson, M., *Seeing red over logging in land of rare parrot.* 2009, Sydney Morning Herald. http://www.smh.com.au/text/articles/2009/05/31/1243708350538.html.
17. West, P., et al., *Firewood harvest from forests of the Murray-Darling Basin, Australia. Part 1: Long-term, sustainable supply available from native forests.* Biomass and Bioenergy, 2008. **32**(12): p. 1206-1219.
18. Chester, S., *River red gums & superb parrots*, in *Bush Telegraph Magazine, Spring/Summer 2009 (Available at: http://www.dpi.nsw.gov.au/aboutus/news/bush-telegraph-magazine/spring-2009/river-red-gums--and--superb-parrots).* 2009.
19. West, P., et al., *Firewood harvest from forests of the Murray-Darling Basin, Australia. Part 2: Plantation resource required to supply present demand.* Biomass and Bioenergy, 2008. **32**(12): p. 1220-1226.
20. Curtis, D. *Supplying Firewood from Farm Forestry Woodlots and Reducing the Greenhouse Effects of Burning Firewood Through Re-vegetation Initiatives*. in *Armidale Firewood Conference 2001*. 2001: Tasmanian Conservation Trust, 2003. (available at: http://www.deh.gov.au/land/publications/firewood-conferences/).
21. DAFF, *Australian forest profiles: Plantations*. 209, Australian Government Department of Aguriculture, Fisheries and Forestry. Available at: http://www.daff.gov.au/brs/publications/series/forest-profiles/australian_forest_profiles_plantationd (accessed January 2010).
22. ABS, *3236.0 - Household and Family Projections, Australia, 2001 to 2026*. 2004, Australian Bureau of Statistics, Canberra.
23. Johansson, L.S., et al., *Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets.* Atmospheric Environment, 2004. **38**(25): p. 4183-4195.
24. Todd, J.J. and M. Greenwood, *Proposed Changes to AS/NZS 4013 – Determination of Particle Emissions Factors*. 2006, Commissioned study for the Commonwealth Department of the Environment and Heritage. Available at: http://www.environment.gov.au/atmosphere/airquality/publications/particle-emission-factors.html.
25. Mann, M. and P. Spath, *A life cycle assessment of biomass cofiring in a coal-fired power plant.* Clean Technologies and Environmental Policy, 2001. **3**(2): p. 81-91.
26. De, S. and M. Assadi, *Impact of cofiring biomass with coal in power plants–A techno-economic assessment.* Biomass and Bioenergy, 2009. **33**(2): p. 283-293.
27. Tillman, D., *Biomass cofiring: the technology, the experience, the combustion consequences.* Biomass and Bioenergy, 2000. **19**(6): p. 365-384.

28. CCSD, *Power Stations Emissions Handbook*. 2009, Cooperative Research Centre for Coal in Sustainable Development (Available at:http://www.ccsd.biz/PSE_Handbook/5/3/, accessed 19 Nov 2009).
29. DCC, *Australia's national greenhouse accounts, National Inventory Report 2007 Volume 1, The Australian Government Submission to the UN Framework Convention on Climate Change*. 2009, Department of Climate Change, Commonwealth of Australia. (Available at: http://www.climatechange.gov.au/~/media/publications/greenhouse-acctg/national-inventory-report-vol-1-part-a.ashx).
30. Pellet Fires Tasmania, *Tasmanian Pellet Fire Technology*. 2009, http://www.pftas.com.au/pages/pellet_heating.html (accessed November 2009).
31. Solar Project, *Solar Armidale Project (www.3sc.net/solarm)*. 2001.
32. Fuller, K., *Smoke gets in your eyes ... and lungs ...* 2008, ABC New England (available at: http://blogs.abc.net.au/nsw/2008/07/smoke-gets-in-y.html?program=new_england_mornings).
33. Khan, L., K. Parton, and H. Doran, *Cost of Particulate Air Pollution in Armidale: A Clinical Event Survey.* Environmental Health, 2007. **7**(2): p. 11-21.
34. Shindell, D. and G. Faluvegi, *Climate response to regional radiative forcing during the twentieth century*. 2009. **2**(4): p. 294-300.
35. Arneth, A., et al., *Clean the Air, Heat the Planet?* Science, 2009. **326**(5953): p. 672-673.
36. NSWDECC, *Air Emissions Inventory for the Greater Metropolitan Region in NSW http://www.epa.nsw.gov.au/air/airinventory.htm*. 2007, New South Wales Department of Environment and Climate Change.
37. Fisher, G., et al., *Health and Air Pollution in New Zealand, Final Report*. 2007, Health Research Council of New Zealand & Ministry for the Environment & Ministry of Transport.

Fig 1. Relationship between particle and methane emissions for eucalypts[4] and softwood[23]

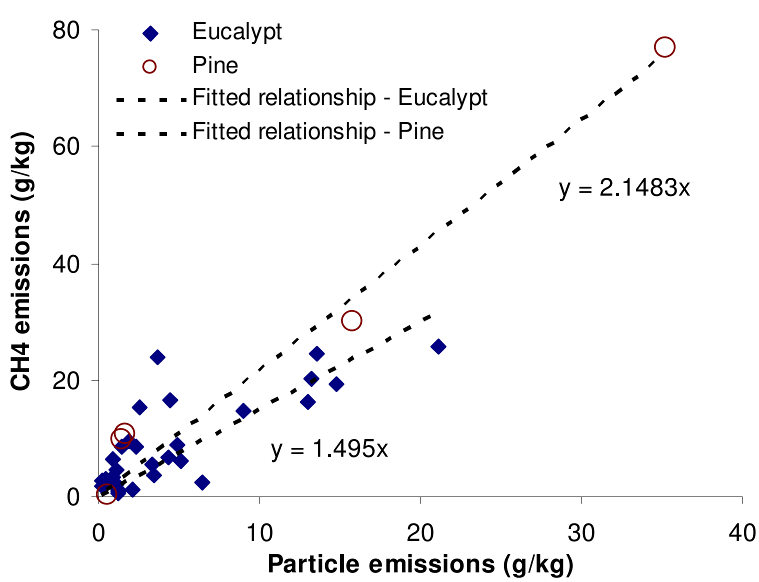

Table 1. Estimated Global Warming Potentials (GWP) for methane (CH_4) and carbon monoxide (CO), and CO_2-eq (g) from burning 1 kg firewood

	IPCC 4th Assessment Report (AR4)			Shindell et al. (2009)[d]	
Emission	100-years		20-years	100-years	20-years
CH_4	25	25	72	33	105
CO	0[b]	1.9	1.9[c]	5	19
18.7 g CH_4 + 200 g CO[a]	468	848	1726	1617	5764
Multiple of AR4, zero CO	1.00	1.81	3.69	3.46	12.33

[a] Real-life emissions studies (see text) show that burning 1 kg firewood will result in 18.7 g CH4 and 200 g CO.
[b] Ignoring CO (not covered by the Kyoto protocol)
[c] A value of 1.9 was used for CO over 20 years – no estimate was found in AR4[3].
[d] Shindell's models[11] have higher uncertainties (e.g. 25 to 40 for 100-year CH_4)

Table 2. Greenhouse gas emissions from gas, electric and wood heating in Australian Cities

City	GJ heat	Flued gas CO_2	Reverse cycle electric CO_2	Wood (living area): Firewood tonnes (GJ)	Wood (living area): CH_4 CO_2-eq (A)	Wood (living area): CO_2 (B)	Electric heat for other rooms (C)	Wood Sustain sourced A + C	Wood A + B + C
Brisbane	3.6	0.3	0.3	1.1 (11)	0.5	2.2	0.2	0.7	2.9
Perth	6.9	0.5	0.6	2.5 (24)	1.2	5.0	0.4	1.5	6.5
Sydney	12.3	0.9	1.0	1.9 (18)	0.9	3.8	0.7	1.6	5.4
Melbourne	34.3	2.6	3.6	4.3 (41)	2.0	8.6	2.5	4.5	13.1
Canberra	39.6	3.0	3.1	3.7 (36)	1.7	7.4	2.2	3.9	11.3
Wted ave*	23.7	1.8	2.3	3.2 (31)	1.5	6.4	1.6	3.1	9.6

Annual heating requirements and CO_2 emissions from gas and electric heating for a 160 square metre house with insulated ceiling from Choice.[13] Average firewood burned, from BDA.[14] 1 tonne of firewood contains about 16 GJ energy, so assuming 60% average efficiency, about 9.6 GJ is delivered to the living area.
(A): CO_2-equivalent from methane calculated as 468 kg per tonne of firewood (see text & Table 1).
(B): CO_2 emissions = 2 tonnes per tonne of firewood.[4] (C): CO_2 emissions for supplementary heating of other rooms calculated as 20% of the estimate by Choice[13] for radiant electric heating for a 160 m^2 house.
*The weighted average was intended to show the effect of replacing an average wood heater by alternatives, so the weighting was according the amount of firewood burned, estimated by particle emissions (Bris 1%, Perth 12%, Sydney 34%, Melb 50%, Canberra 5%, see Table 3) which are proportional to the amount of firewood burned in each city.

Table 3. Estimated health costs per wood heater per year

	Emissions tonnes PM	% of total	wood use tonnes/heater	kg PM2.5/ heater/year	health costs per kg PM	health costs/ heater/year
Brisbane/SEQld	89	1%	1.1	13.8	$43.11	$593
Perth	1600	12%	2.5	31.3	$80.21	$2,507
Sydney	4830	34%	1.9	23.8	$133.54	$3,172
Port Phillip	6904	50%	4.3	53.8	$128.31	$6,897
Canberra	640	5%	3.7	46.3	$81.85	$3,785
Wted ave*			3.2	40.3	$121.71	$4,936

Source BDA[14] assuming 12.5 kg PM2.5 (see text) per tonne of firewood,

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