Human health consequences of reducing emissions of climate altering pollutants

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Abstract

Efforts to reduce global warming often generate significant health benefits. For example, 16 measures recommended by the UN Environment Program and World Meteorological Association (UNEP/WMO) to reduce short-lived greenhouse pollutants (methane (CH_4), black carbon (BC) and ozone precursors) are predicted to avoid 2.4 million premature deaths from air pollution and reduce future warming by 0.4–0.5 °C. Key UNEP/WMO recommendations include replacing traditional biomass and coal stoves in developing countries with clean-burning ones, recovery and use of vented gas during oil and gas production, reducing gas pipeline leaks, collection and utilization of CH_4 from landfills, and separation and treatment of biodegradable waste (recycling, composting and anaerobic digestion) instead of sending it to landfill. Reducing major sources of particulate pollution (diesel engines, coal-fired power and domestic wood-heaters) partly through increased energy efficiency, and encouraging walking and cycling to replace short car journeys are also predicted to improve health and reduce global warming. Compared with climate benefits, the health co-benefits are more local and can be achieved more quickly and directly, making them more tangible and attractive to policymakers and the public. For electricity, estimated health benefits considerably offset the cost of greenhouse-gas mitigation, especially in India, which has high pollution and low mitigation costs. In Australia, improved efficiency, better regulation and replacing coal-fired power with renewables are also estimated to cost less than pollution from coal-fired power. The total health and environmental cost of not addressing global warming are generally considered to exceed the cost of researching, developing and implementing effective measures to reduce climate change.

Keywords: Health, Global warming, Methane, Black carbon, Greenhouse-gas emissions, Biomass, Power generation

Review Methodology: The following sources were searched: existing reviews and reports on the subject; textbooks; CAB Abstracts; Medline; Web of Science; Google Scholar; Google. In addition, the references from the articles obtained by this method were used to check for additional relevant material. Much of the work was carried out before the publication of IPCC AR5 WGII, but the review has been updated to include its salient findings. The results of the identified articles are reported, but it was not possible to subject their methodologies, assumptions and data to a full critical evaluation.

Human Health Consequences of not Addressing Climate Change

The IPCC's Fifth Assessment Report (AR5) concluded that if climate change continues as projected until mid-century, the major increases of ill-health will be greater risk of injury, disease, and death due to more intense heat waves and fires (very high confidence), increased risk of undernutrition from diminished food production in poor regions (high confidence), consequences for health of lost work capacity and reduced labour productivity in vulnerable populations (high confidence), increased risks of food- and water-borne diseases (very high confidence) and vector-borne diseases (medium confidence). In contrast, there could be modest improvements in cold-related mortality and morbidity for some areas because of fewer cold extremes (low confidence), geographical shifts in food production, and reduced capacity of disease-carrying vectors because of exceedance of thermal thresholds (medium confidence). Positive effects will be outweighed, worldwide, by the magnitude and severity of the negative effects of climate change (high confidence). AR5 also noted that all major climate altering pollutants (CAPs) other than CO_2 have near-term health implications (very high confidence) and that in 2010, more than 7% of the global burden of disease was due to inhalation of these air pollutants (high confidence) [1].

A WHO Bulletin review emphasized the importance of adapting to climate change: '*many of the projected impacts on health are avoidable, through a combination of public health interventions in the short term, support for adaptation measures in health-related sectors such as agriculture and water management, and a long-term strategy to reduce human impacts on climate*' [2]. For example, according to a WHO report in 1999, malaria's annual death toll of about 1 million could be halved for an annual cost of $1.25 billion or less by measures such as residual home spraying, insecticide-treated bednets, improved case management and more comprehensive antenatal care [3]. Implementing basic public health measures, e.g. provision of clean water and sanitation, essential health care including vaccination and child health services, increased capacity for disaster preparedness and response, and the alleviation of poverty were considered by AR5 to be the most effective adaptation measures [1].

An opinion piece by Indur Goklany argued that in industrialized countries more people die in winter than summer, substantially due to seasonal increases in deaths from stroke and cardiovascular disease [4] and that the estimated benefits of measures to reduce global warming must be offset against any adverse effects, including the economic costs of mitigation. Goklany estimated that 13% of mortality from hunger, malaria and extreme weather events (including flooding from sea level rise) will be due to global warming.

Economist Nicholas Stern's review for the UK Government described global warming as 'the greatest and widest-ranging market failure ever seen' [5]. Stern estimated the 'business as usual' (BAU) scenario would lower global welfare by the equivalent of a 5–20% reduction in per capita consumption [5]. Predicted consequences of BAU included melting glaciers that initially increase flood risk, and then strongly reduce water supplies, eventually affecting one-sixth of the world population. Global warming was also predicted to reduce crop yields especially in Africa and could leave hundreds of millions unable to produce or purchase sufficient food. Also predicted were increased deaths from malnutrition and heat stress, offset by decreased cold-related deaths at higher latitudes, rising sea levels and sudden shifts in weather patterns. The poorest countries and people were predicted to suffer earliest and most [5], although global warming also increases heatwaves and associated deaths, as well as the risk of bushfires, in developed countries such as Australia [6].

Stern's estimates of the economic costs of climate change were considered to be an outlier by Tol, who noted that higher discount rates tend to produce lower estimates of the cost of emissions [7]. In a follow-up paper, Stern justified his discounting rate, asking if it would be better to invest at 6–7%, then use the accumulated funds to overcome the problems of climate change later, rather than spending money now: '*the price of environmental goods will likely have gone up very sharply, so that our returns from the standard types of investment will buy us much less in reducing environmental damage than resources allocated now (see also Section I on the costs of delay)*' [8]. Health costs in particular are problematical because, even though prevention and better nutrition can help reduce the incidence of disease, healthcare costs are growing rapidly [9] and future generations are likely to value an additional year of healthy life at least as much (adjusted for inflation) as today.

DARA (an independent organization committed to improving the quality and effectiveness of aid for vulnerable populations) was commissioned by 20 governments to research the impacts of climate change, which they estimated was causing 400 000 deaths in 2010 (diarrhoea 85 000; heat and cold 35 000; hunger 225 000; malaria and vector-borne diseases 20 000; meningitis 30 000; environmental disasters 5000) [10]. The accompanying methodology lists an additional 20 000 deaths from skin cancer, but indicates that results for 2010 were based on predictions that temperatures would be about 0.5 °C higher in 2010 than 1990 [11] instead of the actual value of about 0.3 °C [12]. DARA's results are therefore likely to have overestimated the current health problems from global warming.

The IPCC AR5 used the rate of warming from 1998 (a strong El Niño year) to 2012 to illustrate that trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends [13]. Climate models that ignore the phase of the El Niño/Southern Oscillation (ELSO) overpredict current temperatures [12], but models in phase with ELSO are reported to provide good estimates of the observed data [14]. Heat stored in the oceans accounts for 93% of warming since 1955 [15]; sea levels are rising by approximately 3 mm/year because of thermal expansion and melting ice [16]. Strong Pacific trade winds are reported to be increasing subsurface ocean heat uptake; rapid warming (of the land) is expected to resume once the anomalous wind trends abate [17].

In addition to the cost of climate change, DARA estimated that carbon-intensive economies (CIE) cause 3.1 million premature deaths from indoor smoke, 1.4 million from ambient air pollution and 55 000 from occupational hazards [10]. A similar estimate of deaths in 2010 due to household air pollution from solid fuels (3.5 million) was reported in *The Lancet*'s Global Burden of Disease (LGBD), but the LGBD estimate of deaths from ambient air pollution was much higher (3.2 million). The latter was based on improved estimates of PM2.5 pollution using remote sensing, global chemical-transport models and greater coverage of surface measurements [18], as well as new estimates of integrated exposure–response functions [19].

The LGBD excluded global climate change from its assessment for 2010 because available information was considered insufficient to quantify its effects [19]. In contrast, DARA estimated that the no-action scenario would entail climate-change costs equal to 2.1% of World GDP from 2010 to 2100 plus 1.8% for CIE costs [10]. The methodology assumed a 3% discount rate and that economic development would lead to a reduction in deaths from malaria (44% in Africa, 50% in SE Asia and 47% in other low-income countries) by 2030 because of improved management and prevention strategies, with smaller improvements for deaths from malnutrition (8–20%) but little impact of economic development on diarrhoea (7% reduction in Africa, 17% increase in SE Asia and 5% increase in other low-income countries) [11]. Estimated mitigation costs of the 450 ppm scenario (designed to limit the global temperature increase to 2 °C) were 1.1% of GDP, climate-change costs 1.3% of GDP and CIE costs of 0.4% of GDP [10].

Emphasizing Health Co-benefits

In 2009, the UK Academy of Medical Science noted that, rather than conflicting with development goals, the provision of clean energy to low-income countries can help meet both climate protection goals and global health targets [20]. A year later, the Interacademy Medical Panel (IAMP, a global network of academies of medicine, and medical sectors of academies of science and engineering) suggested that, unlike the more long-term effects on the climate, the health co-benefits are more local and can be realized more quickly and directly, making them more tangible and attractive to both to policymakers and the public. Improvement of health could therefore be an important issue motivating climate change mitigation measures [21].

Greenhouse Mitigation Strategies that also Improve Health

The IPCC's AR4 lists sources of global greenhouse-gas emissions in 2004: energy supply 25.9%, industry 19.4%; forestry (including deforestation) 17.4%; agriculture 13.5%; transport 13.1%; residential and commercial buildings (including traditional biomass use but not energy supply) 7.9%; waste and wastewater 2.8% [22]. Health co-benefits of reducing greenhouse missions were investigated by a task force that examined the major contributing sectors to climate change in high-income and low-income countries. The results were published in *The Lancet* as a series of case-studies investigating the costs and benefits of mitigating emissions from short-lived greenhouse pollutants, household energy, electricity generation, urban transport and agriculture [23].

Short-lived Greenhouse Pollutants

The Copenhagen and Cancun meetings of the United Nations Framework Convention on Climate Change (UNFCCC) agreed in 2009 and 2010 that the global average temperature increase should be kept below 2 °C [24] and to consider limiting it to 1.5 °C [25]. Projections (by the UN Environment Program and World Meteorological Association, UNEP/WMO; Figure 1) suggest that the 2 °C target will be exceeded by 2050, unless measures are implemented to reduce powerful shorter-lived greenhouse pollutants (SLGP) including BC, methane (CH_4) and other ozone precursors, as well as reducing CO_2 emissions [26]. Based the latest estimates of its Global Warming Potential, 1 kg of CH_4 causes 84 to 88 times as much global warming as 1 kg of CO_2 in the first 20 years after emission, but (because CH_4 does not stay in the atmosphere as long as CO_2), the overall effect over 100 years is only 28 to 35 times as much [27, 28]. Reducing CH_4 and other SLGP emissions therefore reduces current warming and short-term (or near-term) future warming, with lesser impacts over periods such as 100 years.

UNEP/WMO screened more than 2000 measures to produce a list of 16 recommendations to reduce global CH_4 emissions by 38% and BC emissions by 77% relative to a 2030 reference scenario. Full implementation of the identified measures was predicted to reduce future warming by 0.4–0.5 °C and premature deaths by 2.4 million (range 0.7–4.6 million) and avoid the loss of 32 million tonnes of maize, rice, soybean and wheat production per year (range 21–57 million tonnes, 1–2% of global production). About half of the emissions-reduction for both CH_4 and BC could be achieved by measures expected over their lifetime to deliver financial savings in addition to the economic gains from improved health, climate, crop yield and ecosystem impacts [26]. Table 1 summarizes recommended measures with low or medium cost. In the light of subsequent research that BC emissions may have been under-estimated by a factor of 2–3 [29], the benefits could be even larger than predicted by UNEP/WMO.

The UNEP/WMO research was conducted by a committee of 50 scientists, chaired by Dr Drew Shindell, Coordinating Lead Author of the 'Anthropogenic and Natural Radiative Forcing' chapter of the IPCC's Fifth Assessment Report. Shorter timescales are considered

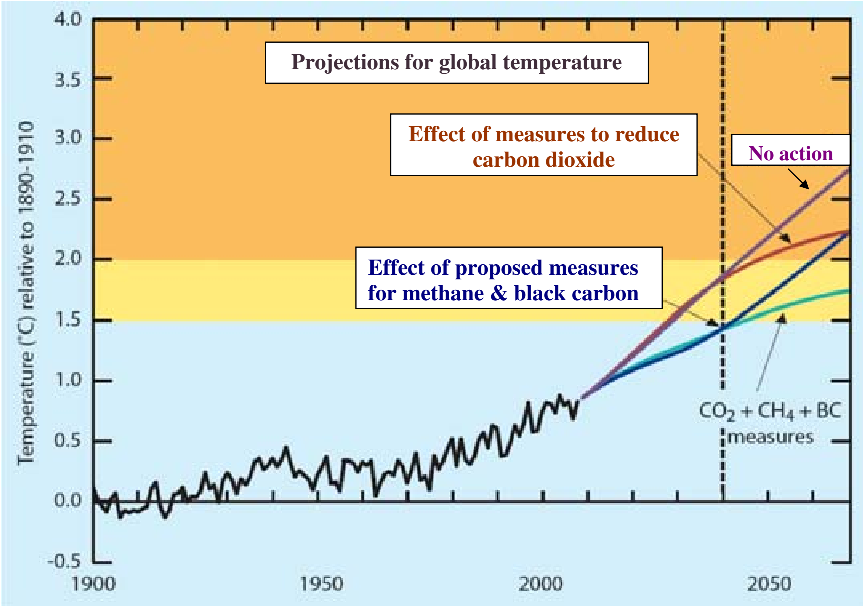

Figure 1. UNEP/WMO projections of global temperatures under (1) business as usual/no action, (2) implementation of the 16 UNEP/WMO recommendations to reduce methane (CH_4) and black carbon emissions (BC), (3) implementation of CO_2 measures in the IEA World Energy Outlook 2009 450 Scenario (IEA450CO_2) and (4) implementation of both the 16 UNEP/WMO measures and IEA450CO_2 (source: UNEP/WMO report [26]) These projections illustrate the difference between the 3 strategies, but as noted in the text, results based on climate models that ignore the phase of the El Niño/Southern Oscillation may not accurately predict the magnitude of the temperature anomaly at a particular time [12, 14].

important because: '*Near-term warming is pushing natural systems closer to thresholds that may lead to a further acceleration of climate change. For example, the melting of permafrost in the Arctic is releasing additional quantities of methane into the atmosphere, which in turn contribute to additional global warming.*' [26]. The IPCC notes that global warming will very likely lead to enhanced CH_4 emissions from both terrestrial and oceanic clathrates (gas molecules trapped in ice) and that estimates of feedback from destabilization of CH_4 clathrates in the twenty-first century are small but not insignificant; catastrophic release of CH_4 during the twenty-first century was considered very unlikely [28a].

Whiteman *et al.* evaluated the effect of 50 Gt CH_4 emitted from the Arctic, either suddenly, or steadily over 50 years using the PAGE09 model. The estimated increase in global temperature of 0.6 °C was estimated to cost $60 trillion (equivalent to 1.7% of world GDP if emitted steadily of 50 years) [30, 31]. In response to questions about the plausibility of a 50 Gt emission [32], the authors defended their research saying that the current ice-free season over the Siberian shelf is sufficient for solar irradiance to create warming up to 7 °C extending the 50 m or so to the seabed and that the mechanism causing the observed mass of rising CH_4 plumes in the East Siberian Sea (on par with previous estimates of CH_4 venting from the entire World Ocean [33]) is unprecedented; the scientists who dismissed the idea of extensive CH_4 release in earlier research were simply not aware of the new mechanism [31].

Clean Cooking for Developing Countries

Switching to LPG/biogas and clean-burning biomasss stoves in developing countries was predicted to achieve 25% of the total reduction in BC emissions from the UNEP/WMO recommendations. About 3.5 million people die prematurely from illness attributable to household pollution from solid fuel use [19]. In India, estimated benefits of a cookstove programme included reduced acute lower respiratory infection in children, chronic obstructive pulmonary disease, and ischaemic heart disease representing 12 500 fewer disability-adjusted life-years (DALYs), plus a saving of 0.1–0.2 megatonnes (Mt) CO_2-equivalent (CO_2e) per million populations in 1 year [34]. Research into the type of stoves indicated that forced draft biomass stoves are more effective in reducing emissions than other types of improved biomass stoves [35].

A Nepalese programme focused on replacement with biogas stoves. After installation, women reported decreases in eye infections (40%), respiratory diseases (24%), coughs (26%) and headaches (41%) [36]. The installations saved an average of 94 min per day: 82 min collecting firewood or preparing dung cakes, 43 min of cooking time and 25 min cleaning utensils, offset by 30 min feeding the biogas digester, and increases of 3 and 22 min, respectively, caring for livestock and fetching water. Biogas installation was reported to motivate households to construct toilets (which are increasingly being connected to the biogas plant) and so improve sanitation and reduce

Table 1 Low and medium-cost measures to reduce BC and CH_4 emissions recommended by the UNEP/WMO as part of their package of 16 measures to reduce global warming by 0.4 to 0.5 °C and avoid 2.4 million premature deaths (source: UNEP/WMO report [26]).

	Emissions reduction potential in 2030	Equivalent price per tonne[2] (variation across regions)		Non-climate benefits
Low-cost measures				
Developing countries: a) clean burning stoves instead of conventional biomass stoves and/or b) clean fuel (LPG/biogas) instead of biomass stoves	1.8 Mt BC 24.8%[1]	a) −\$10,100/t BC (−12,000 to −5,000) b) −\$200/t BC (−240 to −100)	−\$6/t CO_2e (−7 to −3) \$7 t CO_2e (6 to 14)	Health protection, indoor air quality, crop protection
Recovery and utilization of vented associated gas during oil production	30.6 Mt CH_4 10.8%	−\$150/t CH_4 (−730 to 480)	\$70/t CO_2e (32 to 92)	Energy efficiency, crop protection
Separation and treatment of biodegradable municipal waste with no biodegradable waste disposed of to landfill	27.8 Mt CH_4 9.7%	−\$1,650/t CH_4 (−1,840 to −1,450)	\$29/t CO_2e (12 to 53)	Improved waste management, energy efficiency, crop protection
Replacing coal with coal briquettes in cooking and heating stoves in developing countries	0.4 Mt BC 3.9%	Approximately zero cost /t BC and CO_2e		Health protection, crop protection
Reduced leakage during gas pipeline transmission	6.7 Mt CH_4 2.3%	−\$190 \$/t CH_4 (−259 to 4,120)	\$27/t CO_2e (21 to 382)	Long-term economics, energy efficiency, crop protection
Recovery and utilization of vented associated gas during gas production	2.4 Mt CH_4 0.85%	−\$690/t CH_4 (−721 to −632)	−\$7/t CO_2e (−8 to −6)	Long-term economics, energy efficiency, crop protection
Farm-scale anaerobic digestion on large farms with liquid manure management	2.2 Mt CH_4 0.7%	−\$400/t CH_4 (−2,320 to +1,250)	\$34/t CO_2e (17 to 81)	Energy efficiency, crop protection
Replacing traditional brick kilns with more efficient kilns	0.04 Mt BC 0.5%	−\$5,500/t BC (−5,600 to −4,400)	−\$7/t CO_2e (−5 to −8)	Improved quality of bricks, health protection, energy efficiency
Medium-cost measures				
Coal mines: oxidation of ventilation air methane including improvements in ventilation air systems	25.0 Mt CH_4 8.7%	\$280/t CH_4 (222 to 2,820)	\$13/t CO_2e (11 to 137)	Occupational safety
Coal mines: recovery of pre-mine degasification emissions	17.5 Mt CH_4 6.1%	\$1,300/t CH_4 (500 to 10,500)	\$74/t CO_2e (37 to 445)	Occupational safety, energy efficiency
Feed changes for dairy and non-dairy cattle	3.9 Mt CH_4 1.3%	\$1,330/t CH_4 (1,090 to 1,880)	\$53/t CO_2e (44 to 75)	Improved meat quality
Replacing traditional coke ovens with modern recovery ovens	0.2 Mt BC 1.6%	\$190/t BC (140 to 500)	\$0.4/t CO_2e (0.3 to 1.1)	More cost-effective production, energy efficiency

[1] Percent of total temperature reduction that could be achieved in 2050 by the package of 16 measures. [2] Values are global means, with variation across regions shown in parentheses. Prices expressed in \$US per tonne of BC or CH_4 emissions (negative values imply a saving) from a social planner's perspective assuming a 4% discount rate. Costs per tonne of CO_2e (based on the GWP_{100} metric) take account of co-emitted species and are from a private investor perspective assuming a 10% discount rate.

the risk of worms, bacterial and viral infections. Use of digester slurry to replace raw dung and chemical fertilizer also helps improve crop productivity. Firewood collection is the major cause of deforestation in Nepal. As well as helping to conserve forests, the average household biogas system avoids the emission of about 4.5 tonnes of CO_2e. In 2009, Nepal's earning through the World Bank Voluntary Emissions Reduction Scheme were estimated at over US$600 000 per year [36].

Reducing biomass emissions is likely to generate additional health benefits. In Belize, Kenya, Nepal and American Samoa, observation and cognitive function tests on 3–9-year-old children showed that, compared with kerosene stoves, open-fire cooking was associated with lower cognitive performance and less frequent structured play at all ages ($P < 0.001$ for most cognitive function tests and age groups) [37]. A study in Guatemala also reported a link between exposure to woodsmoke (determined by carbon monoxide levels measured in the women's homes during the third trimester of pregnancy) and lower performance of children at age 6 and 7 on neurodevelopmental tests of visuo-spatial perception and integration, visual-motor memory, and fine motor skills ($P < 0.05$) [38]. It is hypothesized that such impairments in cognitive function relate to the polycyclic aromatic hydrocarbons (PAH) in woodsmoke. In New York, children of mothers exposed during the third trimester of pregnancy to more than the median of 2.26 ng/m^3 PAH averaged 4.7 and 4.3 points lower (P=0.007 and 0.003, respectively) on verbal and full-scale IQ tests when they started school [39]. Both maternal PAH exposure and the presence of detectable DNA adducts specific to benzo[a]pyrene (a representative PAH), in maternal and umbilical cord blood, were positively associated with symptoms of anxious/depressed and attention problems ($P \leq 0.05$) [40].

Benefits of Reducing BC and CH_4 Emissions in Developed Countries

UNEP/WMO recommended several low-cost measures to reduce CH_4 emissions, including recovery and utilization of vented gas during oil and gas production, reduced leakage during gas pipeline transmission, separation and treatment of biodegradable waste (recycling, composting, anaerobic digestion instead of sending it to landfill) and anaerobic digestion on large farms with liquid manure management. Medium-cost CH_4 measures were the recovery of pre-mine degasification emissions, oxidation of ventilation air CH_4, and feed changes for cattle. Apart from the latter (expected to improve meat quality) and ventilation of mines (improving occupational safety) improved energy efficiency and crop protection were considered to be the main benefits, rather than health [26].

In contrast, the recommended measures for reducing BC were expected to improve health, but involve higher costs. They included use of diesel particle filters to achieve Euro-6 standards (costing $36 000–150 000 per tonne of avoided BC emissions for light-duty vehicles), and phasing out log-burning heaters in developed countries ($200 000–400 000 per tonne of avoided BC emissions) [26]. The costs of eliminating high-emitting vehicles and bans on open burning of agricultural waste were considered difficult to quantify, because of their dependence on strong governance and regulatory frameworks for successful implementation [26]. However, the many instances around the world where such measures have been successfully implemented were cited as evidence that costs are not a major barrier [26]. Subsequent research estimated the total climate forcing of BC at +1.1 W/m^2, making BC the second most important anthropogenic emission in terms of climate-forcing in the present-day atmosphere, with only CO_2 estimated to have greater forcing [41]. However, the total contribution to global warming from any particular source depends on the mix of co-emitted pollutants. Although some organic aerosols appear to have a net cooling effect [41], emissions from cookstoves in India were also found to contain organic aerosols of brown carbon, which absorbs in the near-UV region of the solar spectrum and adds to the warming from BC [42]. Professor Piers Forster, coordinating lead author of the 'Changes in Atmospheric Constituents and in Radiative Forcing' chapter of the IPPC AR4 [43], commented: '*Reducing emissions from diesel engines and domestic wood and coal fires is a no-brainer as there are tandem health and climate benefits. If we did everything we could to reduce these emissions we could buy ourselves up to half a degree less warming, or a couple of decades of respite*' [44].

As well as BC, domestic wood-heaters in Australia were noted to produce substantial quantities of CH_4 [45]. Even over a 100-year assessment horizon, CH_4 emitted from domestic wood-heaters was estimated to cause substantially more global warming than heating the same house with gas or an electric heat pump [45]. Consequently, Australia's annual contribution to global warming could be reduced by at least 8.7 million tonnes of CO_2e if the 4.75 tonnes of wood currently burned in domestic wood-heaters was used to partially replace coal in power stations, and homes instead heated by gas or electric heat pumps [45]. The amount of wood used to replace coal should ideally be limited to what can be sustainably harvested without reducing biodiversity or the amount of carbon stored in trees; there are concerns that current firewood use is unsustainable [46]. Domestic wood-heaters emit a disproportionate amount of health-hazardous pollution (e.g. wood is the main heating for 2.5% of Canberra households [47], but domestic woodsmoke represents 69% of the city's PM10 and 66% of PAH emissions [45, 48]) with estimated health costs of thousands of dollars per heater per year, so other uses (power generation, wood pellet heaters) for the limited supply of sustainably produced biomass would improve health as well as reduce global warming [45].

A real-life example of the health benefits was demonstrated by Launceston's woodsmoke-reduction programme, funded by a $2.05 million Australian Federal Government grant. Wood-heater use fell from 66 to 30% of all households, resulting in a 40% fall in 3-month average wintertime particulate air pollution. Compared to 1994–2001, male all-cause mortality fell by 11.4%, with falls of 17.9 and 22.8%, respectively, for male cardiovascular and respiratory deaths [49]. During the winter months (June–August) deaths for males and females combined showed even higher reductions: cardiovascular 20%; respiratory 28% [49]. Knowledge about the health effects has led to a continued decline in wood-heater use to an estimated 15% of Launceston's households [50], but even at this level, the advisory PM2.5 level of 25 $\mu g/m^3$ was exceeded 14 times in 2012 [51]. Woodsmoke levels can vary substantially between residential areas in the same city [52]. In Christchurch, NZ, residents of areas with higher PM10 levels had increased mortality – 8% more total deaths, 11% increased circulatory deaths and 34% increased respiratory deaths for each additional 10 $\mu g/m^3$ of PM10 exposure. Christchurch's most polluted residential areas had up to 20 $\mu g/m^3$ more particulate pollution than the cleanest areas, implying increases of up to 22% in circulatory and 68% in respiratory deaths [53]. In Vancouver, Canada, where annual average PM2.5 concentrations vary from 3.5 to 4.6 $\mu g/m^3$ [54], residential areas in top third for woodsmoke exposure had 15% more hospital admissions for Chronic Obstructive Pulmonary Disease than those in the bottom third [55].

In summary, reducing SLGP (CH_4, BC and O_3 precursors) emissions is expected to improve human health and reduce global warming. The package of 16 measures recommended by UNEP/WMO was predicted to reduce global warming by 0.4–0.5 °C, avoid 2.4 million premature deaths every year from outdoor air pollution by 2030, and help avoid annual crop losses of about 32 million tonnes/year [26]. Adequate institutional and legal frameworks were considered essential for the successful mitigation of SLGP, as well as adequate human, technical and financial resources, including programmes to increase awareness and political support [26]. International organizations and donors can play an important part. Examples include UNEP's Global Fuel Economy Initiative (which has the co-benefit of reducing BC emissions) and the Prototype Methane Financing Facility (PPMF), introduced by the Methane Blue Ribbon Panel with UNEP support. The PMFF provides a guaranteed floor price for certified emission reductions (CERs) arising from qualified methane projects, especially in the less-developed countries and for cookstoves projects that abate CH_4 [26].

Household Energy in Developed Countries

Improving energy efficiency can be a highly cost-effective way to reduce global warming [56]. The Global Energy Assessment found that efficiency improvement was proving to be the most cost-effective near-term option with multiple benefits, such as reducing adverse environmental and health impacts, alleviating poverty, enhancing energy security and flexibility in selecting energy supply options, as well as creating employment and economic opportunities [57].

Hypothetical strategies to improve energy efficiency in the UK housing stock were evaluated in a case study. A combined strategy of improved insulation, ventilation, fuel switching and behavioural changes was estimated to result in 850 fewer DALYs and save of 0.6 Mt CO_2 per million populations per year [58].

In Christchurch, NZ, the Clean Heat Project achieved substantial reductions in energy consumption of 1973 households that received subsidies to replace wood-heaters with reverse cycle air conditioners/heat pumps plus improved insulation and draft-proofing (if needed). Household electricity use increased by just 1% [59], implying that, as well as a substantial reduction in air pollution, CH_4, BC and other greenhouse emissions, families who previously bought several tonnes of firewood per year would have substantially lower heating costs.

Choosing to buy energy-efficient products can also be a worthwhile way of reducing energy consumption and therefore greenhouse-gas emissions. One example is the replacement of a gas-heating system that used 3000 kWh of energy with reverse cycle air conditioners that used just 328 kWh of electricity to heat more rooms to a more comfortable temperature [60].

Electricity Generation

A study published in 2011 concluded that moving away from coal-fired power in the USA was expected to reduce climate change and improve health [61]. Coal was reported to generate just over 50% of electricity but produce 81% of the utility sector's CO_2 emissions [61]. The best estimate, using full-cost accounting, was that the health effects of air pollution from coal-fired power amounted to 9 c/kWh [62], with health impacts of coal mining adding another 4.4 c/kWh and climate-change 3.1 c/kWh [61]. The price of coal-fired electricity was considered to conservatively double or triple if these costs were included, making wind, solar and other non-polluting power, and investments in efficiency and electricity conservation methods, economically competitive [61].

The effects of electricity generation in the European Union (EU), China and India under BAU and two mitigation scenarios were modelled in a study published in 2009 [63]. The POLES model for electricity generation was combined with the GAINS model of the interactions between greenhouse gas and air pollution to show that reducing CO_2 emissions would also reduce PM2.5 pollution and associated mortality, with greatest benefits in

India, and smallest in the EU. Health benefits were found to considerably offset the cost of greenhouse-gas mitigation, especially for India, which has high pollution and low mitigation costs [63]. Under BAU, PM2.5 was predicted to increase in India, with years of life lost per million persons (YLL/M) increasing from 19 489 in 2010 to 28 408 in 2030. Carbon trading was predicted to save 1492 YLL/M. For China, YLL/M were predicted to reduce slightly under BAU (from 19 205 in 2010 to 18 488 in 2030), with additional reductions (432 YLL/M) for limited and (542 YLL/M) for full carbon trading.

In the EU, the POLES models predicted that in 2030 under BAU in 37% of power would be generated by coal (without carbon capture and storage, CCS). Under carbon trading, coal-fired power without CCS was predicted to fall to 8% of generation, with 18% from coal with CCS, renewables would remain at 26%, nuclear would increase from 14 to 20%, gas from 15 to 19% (including 25–33% with CCS), biomass from 3 to 4%, others remaining at 5% [63]. Under BAU, pollution-related YLL/M were predicted to fall from 2002 (in year 2010) to 1185 (in year 2030), with an additional reduction of 104 YLL/M (a total saving of 48 000 YLL) under carbon trading. Sensitivity analyses using age-weighting and discounting of future YLL reduced overall estimates of benefits, but had little effect on comparisons between scenarios. Changing the assumed exposure–response relationship from log-linear to linear considerably increased the estimated health benefits of mitigation in India and China.

For the 27 EEC countries, coal-fired power declined from about 39% of generation in 1990 to 25% in 2009 [64] – 15% hard coal, 10% lignite [65], suggesting a faster rate of decline in coal-fired power than predicted by the POLES model [63]. Outdoor air pollution was estimated to cause 492 000 premature deaths in Europe, with coal-fired power responsible for more than 18 200 premature deaths, as well as 8580 new cases of chronic bronchitis, 5498 hospital admissions for respiratory or cardiovascular illness and over 4 million lost working days each year [65]. The health costs of coal combustion in Europe were estimated at up to €42.8 billion per year. Including emissions from plants in Croatia, Serbia and Turkey, the estimated number of premature deaths from coal-fired power increases to 23 300 and total annual costs to €54.7 billion [65].

The cost of air pollution from Australian coal-fired power in 2009 was estimated at about A$13 per MWh. Combined estimates of greenhouse and air pollution costs were A$19/MWh for natural gas, A$42/MWh for black coal and A$52/MWh for brown coal [66]. Two studies modelled a switch to clean 100% renewable electricity. The first (ZCA2020) envisaged generating 60% of electricity by concentrated solar thermal (CST) power with molten salt storage and 40% by wind, plus biomass and hydroelectricity backup. Capital costs averaging A$37 billion per year, 3% of GDP, would be required for 10 years. Ignoring health and climate impacts, ZCA2020 and BAU were projected to have similar costs over 30 years, with potentially greater benefits for ZCA2020 if electricity could also be used to power cars and other transport, leading to fuel costs savings of almost A$1170 billion [67]. BAU was expected to need A$135 billion for ongoing capital investment in energy infrastructure from 2011 to 2020, as well as A$300 billion for fuel over a 30-year period. Including climate benefits and savings from avoided oil imports using electric vehicles for transport, ZCA2020 was predicted to have lower total cost than BAU by 2021, and save A$1550 billion by 2040.

The second study by the Australian Energy Market Operator (AEMO), also considered the market and transmission implications of moving towards 100% renewable energy [68]. AEMO predicted that the transition to 100% renewables would increase the wholesale price of electricity from 5.5 to 11 c/kWh [68], about 20% of the current retail price, remarkably similar to the ZCA2020 estimate of 6.5 c/kWh if the entire project were funded by increased electricity prices [67], and less than the estimated air pollution cost (noted above) of 13 c/kWh. AEMO concluded that onshore wind and photovoltaics (PV) (which continue to improve in efficiency [69, 70]) would have the cheapest installation costs per kW, but only limited periods (30–40% for onshore wind, 15% for PV) producing power at the installed capacity. They considered that 9 h of storage would be more cost effective than the 15 h used in some overseas plants, enabling CST to cover morning and evening peaks and complement PV generation, with geothermal, biomass and hydro filling in at other times. Estimated capital costs to build in 2020 (scenario 1, allowing for rooftop PV, electric vehicles and demand management, with maximum demand of 35 GW in 2030, 40 GW in 2050, total installed capacity of 82.5 GW, including a reserve 102% above the maximum predicted demand) were A$197 billion for generation and storage connections, A$22 billion for transmission upgrades.

New technological developments, such as zinc bromine [71], sodium ion with a tin/wood fibre anode [72], aqueous sodium [73] or lithium [74] rechargeable batteries are expected to reduce the cost of battery storage from US$600 in 2014 to US$310 per kWh [75]. These developments plus storage systems for offshore wind [76], pumped hydro storage to help meet peak demand [77] and CST using super-critical steam [78], could potentially reduce costs and the need for a reserve 102% above maximum predicted demand, and therefore the cost of changing to renewable energy.

Even without a carbon price, wind power is estimated to be 14% cheaper than a new baseload coal-fired power station and 18% cheaper than a new gas one [79], increasing the likelihood, as cost-effective technology develops and improves, of a transition to renewable energy, avoiding health costs and greenhouse emissions. UK National Grid data show that wind power produces up to 4 MW of electricity on windy days, substantially decreasing the need for gas-fired generation on those days (from about 11 000 to <8000 MW) [80]. In Denmark, wind provided 54.8% of all electricity used in December 2013 [81]. In Australia, despite record runs of extreme temperatures (maxima over 42 °C for five consecutive days in Adelaide, four consecutive days with maxima over 41 °C in Melbourne [82]), partly because of a 4.6% reduction in peak demand from rooftop PV, wholesale electricity prices averaged A$509/MWh on January 16 2014, only 11% of the wholesale price of A$4619/MWh during similar heatwave conditions on 29 January 2009 [83]. Hot weather in Adelaide, Melbourne and Canberra is now at levels predicted for 2030 [6].

Regulatory reform could assist the transition to renewable energy by providing incentives to manage peak demand and encourage investment where it will achieve the greatest benefit [84]. Wholesale electricity prices average 20% of Australian consumer electricity bills, compared with 51% for network transmission, including 25% of the total bill to cover network infrastructure investment to meet about 40 h of critical peak demand per year [85, 86]. This suggests that savings from improved energy efficiency and demand management could more than cover the cost of converting to renewable electricity generation. The perverseness of current regulations which encourage excessive investment in infrastructure [87] was noted in 2012 by Australian Energy Minister, Martin Ferguson, who explained that installing an A$1500 air-conditioning system was expected to cost A$7000 in upgrades to the electricity network to ensure sufficient capacity to run the air-conditioner on the hottest summer day [84, 88]. Every dollar spent reducing demand was estimated to save more than two dollars in network infrastructure costs [86]. Perverse regulations also allowed network companies to build and charge consumers for unnecessary infrastructure including an A$30 million substation that was not even connected to the grid [89]. Partly because of increased electricity bills, Australian electricity consumption in the year to September 2013 was 7% below 2008 levels, despite population increases; greenhouse-gas emissions were nearly 16% lower [90]. Industry energy savings of A$3.3 billion were recently identified, many with payback periods of less than 2 years [91]. One remarkable initiative was an A$4.5 million trigeneration system for a community club in Sydney, that reduced annual electricity bills from A$2.5 to 0.75 million [88].

Two Australian coal-fired power stations are reducing emissions by solar-thermal boosting, and another has successfully trialled an innovative biomass pyrolysis process that produces biochar as well as syngas which can be used for electricity generation [92]. Biomass co-firing is another possible option, which could reduce global warming and air pollution compared with using limited supplies of sustainably produced biomass in domestic wood-heaters [45]. Strategically located concentrated solar power installations were also reported to be a commercially viable alternative to traditional network augmentation [93]. In South Australia, volume weighted wholesale electricity prices fell from A$70 to A$80/MWh in 2008–10, to about A$45 in 2011, in parallel to the installation of wind and solar capacity (and the flat-lining of demand) [94]. These and other policies have led to a reduction in Australian coal-fired generation in Australia from 86% in 2008–09 to 75% in 2013 [95]. With regulatory reform to achieve maximum benefit to consumers (including the effect on public health), such innovations could increasingly help improve health by reducing both PM2.5 pollution and global warming.

Transport

Transport-related greenhouse-gas emissions are increasing, especially in low and middle-income countries. A study of transport-related emissions in London and Delhi found that a reduction in CO_2 emissions through increased active travel (walking and cycling) to levels of European cities such as Freiburg, Delft, Copenhagen and Amsterdam) with commensurate reductions in motor vehicle use had larger health benefits per million population (7332 DALYs in London, and 12 516 in Delhi in 1 year) than increased use of lower-emission motor vehicles (160 DALYs in London, and 1696 in Delhi) [96]. Sensitivity analyses, assuming different exposure–response functions for physical activity (reported in an online appendix to the paper) produced a range of estimates for the reduction in DALY ranging from 4980 to 8354 in London and 3633 to 10 415 in Delhi.

The combination of active travel and lower-emission motor vehicles was estimated to provide the largest benefits (7439 DALYs in London and 12 995 in Delhi), notably from a reduction in the number of years of life lost from ischaemic heart disease (a 10–19% reduction in London, 11–25% in Delhi). Although uncertainties remain, especially concerning the exposure–response relationships for air pollution and physical actively, transport-related climate change mitigation is expected to generate substantial public health benefits. Policies to increase the acceptability, appeal, and safety of active urban travel, and discourage travel in private motor vehicles would provide larger health benefits than policies that focus solely on lower-emission motor vehicles [96].

Agriculture

Agricultural food production and agricultural-related change in land use are substantial contributors to greenhouse-gas emissions worldwide, with four-fifths of agricultural emissions arising from the livestock sector, mainly enteric CH_4 emissions [97, 98]. A case study for the UK identified that a combination of agricultural technological improvements and a 30% reduction in livestock production would reduce emissions by 50%. The potential benefits of reduced consumption of livestock products was predicted to reduce the burden of ischaemic heart disease by about 15% in the UK and 16% in São Paulo (2850 DALYs per million population per year in the UK and 2180 in São Paulo) [97]. However, encouraging 'affordable, healthy, low-emission diets for all societies' will probably 'encounter cultural, political and commercial resistance' [97].

In the absence of any changes in diet, the FAO predicts that worldwide demand for meat will double by 2050 [99] and demand for milk will double in the developing world by 2030 [100]. Reducing emissions, despite increasing production, will require a substantial reduction in emissions per unit of product. Achieving this, e.g. by breeding for reduced CH_4 emissions [98, 101] or more efficient production systems [102, 103] will not directly affect human health. Grass-fed meat is generally considered to have a healthier fatty acid profiles [104] and, if grown on pasture that is actively sequestering carbon, reduced greenhouse-gas emissions per unit of product [105], but increased emissions in the absence of pasture sequestration [106]. A large proportion of greenhouse emissions from cattle originate from the cow–calf system (e.g. 80% in Canada [107]), so feedlot and pasture-finished meat are unlikely to differ substantially [108].

Other Strategies with Health Co-benefits

Although population growth rates and total population size are not the sole determinant of emissions, the IPCC WGII cites a study suggesting that CO_2 emissions could be 30% lower by 2100 if access to contraception was provided to women expressing a need [1]. In 2012, satisfying unmet needs in developing countries was expected to prevent 54 million unintended pregnancies, including 21 million unplanned births, 26 million abortions (of which 16 million would be unsafe) and 7 million miscarriages, 79 000 maternal deaths and 1.1 million infant deaths [109].

Other mitigation strategies with health co-benefits include increased urban green space (to reduce noise, temperature and heat island effects, sequester carbon in plants and soil, and enhance self-perceived health status [1]) and carbon sequestration in forest plantations (alleviating poverty and generating employment [1]).

Regulatory Policy

Nicholas Stern's description of global warming as 'the greatest and widest-ranging market failure ever seen' [1] summarizes the problem that traditional market forces cannot recover the cost of global warming from those responsible for greenhouse-gas emissions. Regulations or incentives are therefore needed, together with regular reviews to ensure the desired objectives are achieved, avoiding perverse situations such as the Australian regulations that encouraged network upgrades, despite potentially greater benefits from investing in energy efficiency [88]. Policies and incentives that treat all biomass burning as carbon neutral have also been questioned [110] because of the limited supplies of sustainably produced timber [46] and because forest carbon losses can delay net GHG mitigation [111, 112]. Moreover, burning wood in a way that produces CH_4 or BC results in even more global warming and health problems than other uses (e.g. co-firing) for the limited supplies of sustainably produced biomass [45]. Regulatory policies should therefore consider all consequences and emphasize the 'win–win' options that have the highest benefit cost ratios when greenhouse-gas emissions and health are considered.

Conclusions

In many cases, reducing greenhouse-gas emissions generates significant health benefits from reduced air pollution and increased physical activity. Unlike the more long-term effects on the climate, the health co-benefits tend to be more local and can be realized more quickly and directly. It has been argued that this makes them more tangible and attractive both to policymakers and the public. Increased awareness of the health co-benefits could encourage governments to fund greenhouse-reduction and adaptation strategies in order to reduce health costs. Policies should consider all consequences and emphasize 'win–win' options that have high benefit–cost ratios.

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