COPENHAGEN CONSENSUS CENTER

AIR POLLUTION

PERSPECTIVE PAPER

Benefits and Costs of the Air Pollution Targets for the Post-2015 Development Agenda

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Post-2015 Consensus

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Objectives of this paper

This paper has two objectives:

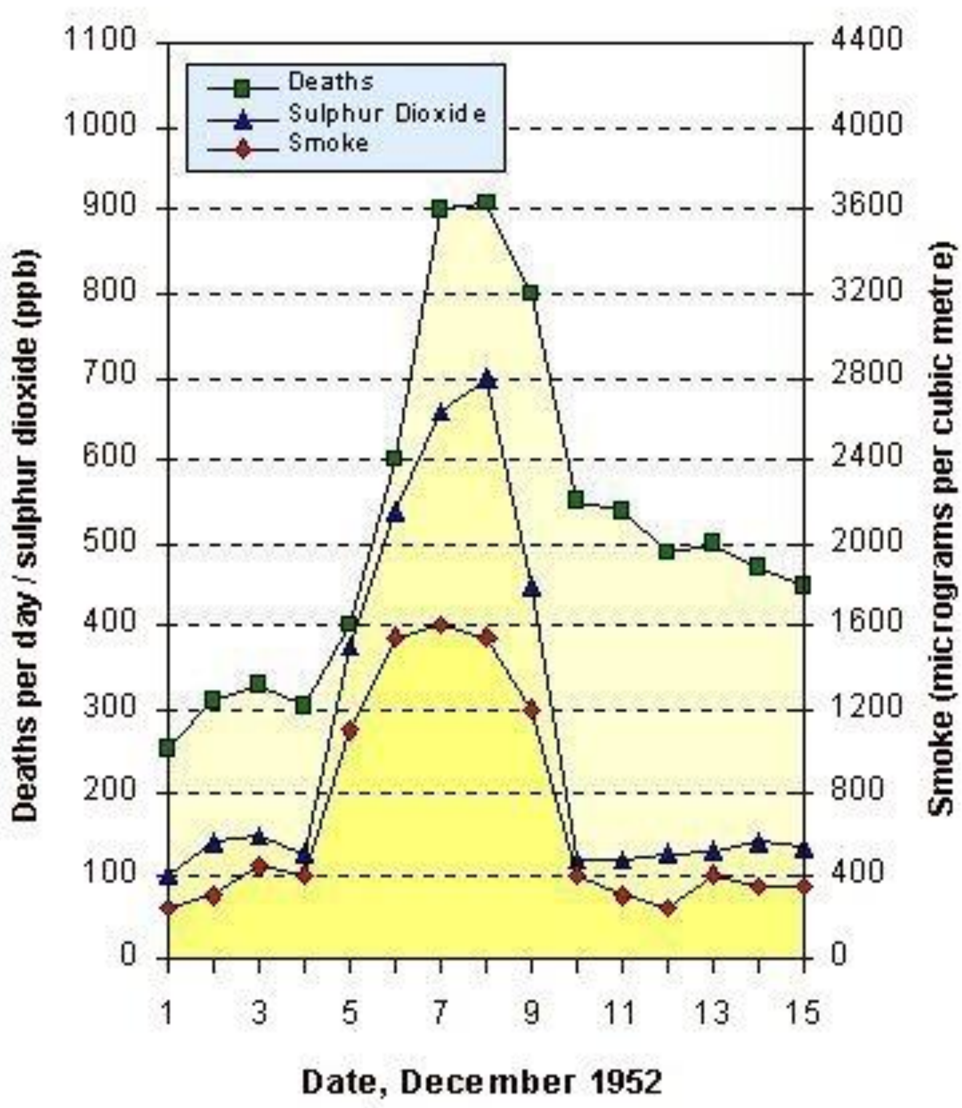
1. To review the assessment paper by Bjorn Larsen of the impacts of household and outdoor air pollution, and of the benefits of air quality improvement. This is the subject of Section 0 of the paper.
2. To provide additional perspectives, in particular relating to opportunities for increasing the efficiency of actions for improving air quality. This is the subject of Section 0 of the paper.

It is also useful to consider how we reached the current position on air quality and understanding of the problem. This is the subject of Section 0, as it provides some background to the later Sections. It will be seen that the problems of countries like China and India, that are undergoing rapid industrialisation fed by coal, are problems previously experienced in countries like the UK. It is to be hoped that lessons on efficient solutions can be learned from these experiences, and that mistakes made earlier are not repeated.

Historical Perspectives

The Great London Smog of December 1952 provided clear evidence that air pollution is harmful to health. It was not the first smog of its kind: they had long been a regular feature of life in London and numerous other cities of the world wherever coal was burned in large quantity. Effects previously had been thought more likely due to the cold weather that provided the conditions for the smog to form and persist. The weather was not particularly cold during the Great London Smog, however, and the very close correlation between pollution levels and mortality was sufficient for the case to be considered causal (Figure 1).

Figure 1. Mortality and air pollution during the Great London Smog of December 1952[1].



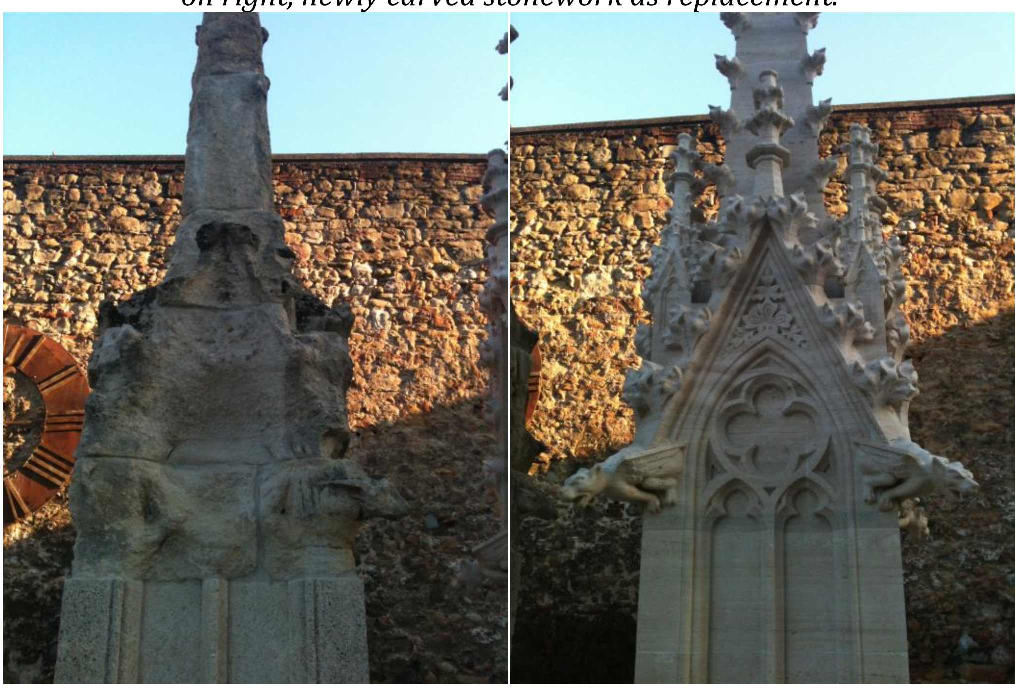
[1] http://www.air-quality.org.uk/03.php.

Legislation followed in the UK through the Clean Air Acts of 1956 and 1968, directed principally at reducing smoke emissions, but addressing SO_2 at the same time because the two pollutants were both products of coal combustion (this feeds through to the concept of co-benefits in Section 0). Similar legislation was passed in other countries experiencing similar problems. The following measures and conditions led to a large reduction in concentrations:

- Introduction of smoke control areas to address domestic emissions;
- Use of cleaner coals with a lower sulphur content;
- Use of tall chimney stacks on power stations;
- Relocation of power stations to rural areas;
- Fuel switching, particularly to electricity and natural gas (the latter helped in the UK by the discovery of large gas reserves in the North Sea);
- Decline in heavy industry (though of course this occurred to a significant extent simply through the relocation of production outside the UK).

By the late 1960s few in the industrialised world considered air pollution to be a problem. However, air pollution returned to public attention in the 1970s through concern over acid rain, particularly through its effects on rivers, lakes and forests and on building materials such as the limestone used in many of Europe's finest buildings (Figure 2).

Figure 2. Damage to stonework at Zagreb Cathedral, Croatia, from acidic deposition. On left, the original stonework showing the decay after reconstruction at the end of the 19th century, on right, newly carved stonework as replacement.



Over time these concerns were accepted and a pan-European programme was initiated through the UNECE Convention on Long Range Transboundary Air Pollution to reduce emissions, first of sulphur and then nitrogen[2]. The USA established NAPAP (the National Acid Precipitation Assessment Programme) at the same time[3]. Subsequently, concerns spread to ozone as well, with additional action taken on VOCs (volatile organic compounds). This group of pollutants (and later fine particles) were considered together because it was recognised that their effects were interlinked, either through direct effects of emitted pollutants or by indirect effects associated with their reaction products.

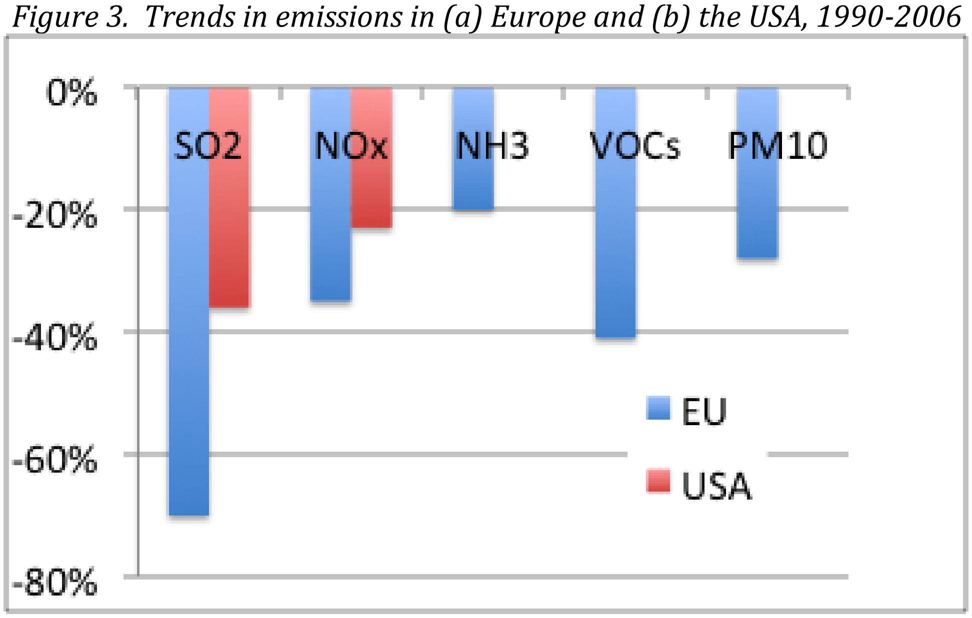
Table 1. Linkages between the major air pollutants regarding their effects.

	NH_3	NOx	PMx	SO_2	VOCs
Acidification	▯	▯		▯	
Eutrophication	▯	▯			
Ozone		▯			▯
Health	▯	▯	▯	▯	▯
Materials		▯		▯	

The presence of these linkages mean that it is inappropriate to consider pollutants in isolation of one another when seeking to develop cost-optimal strategies for dealing with any of the listed impacts.

Emission reductions for sulphur especially have been dramatic in both Europe and the USA[4] (Figure 3, covering the period 1990 to 2006, though there have been further emission reductions before and since), though different policy drivers have been used. In Europe the emphasis has been on technological solutions and the use of low sulphur fuels, whereas in the USA tradable permits have also been used for sulphur control.

Figure 3. Trends in emissions in (a) Europe and (b) the USA, 1990-2006



[2] http://www.unece.org/env/lrtap/
[3] http://www.epa.gov/airmarkets/resource/docs/NAPAP.pdf
[4] http://www.epa.gov/airtrends/aqtrends.html

Health concerns were raised again in the late 1980s. More detailed analysis, was then possible drawing on developments in statistical methods and computing power, and reanalysis of data from London in the 1950s showed that effects were detectable at levels previously thought 'safe'. Importantly, this new analysis found no evidence for the threshold of exposure to (particularly) fine particles. Health has largely taken over as the prime driver of air pollution policies in North America and Europe since the mid 1990s, though work on ecosystem impacts continues, for example through the EU-funded ECLAIRE Project[5]. Much of this new work explores links between effects of NOx and the other pollutants of major interest here, and climate change.

Review of the assessment paper by Bjorn Larsen

The magnitude of impacts

The Assessment Paper describes results from the Global Burden of Disease study[6] demonstrating the substantial impact of air pollution on exposure to fine particles in the indoor and outdoor atmosphere in 2010, leading to nearly 6 million deaths annually across the globe. More recent work by WHO, also noted by Larsen, provides a higher estimate, of 7 million deaths per year[7], with 3.7 million deaths attributed to ambient air pollution (AAP) and 4.3 million deaths to household air pollution (HAP)[8].

Calculation is based on the findings of a very large body of epidemiological literature that has been produced over the last 3 decades, and broad consensus amongst experts internationally. Of special mention in reaching this consensus is the work of the Health Effects Institute (HEI)[9], a joint industry-government body in the USA, and WHO-Europe through the recent REVIHAAP[10] and HRAPIE[11] studies.

A number of issues are worthy of comment in relation to this estimate:

1. That it is based very largely on the epidemiological literature.
2. That it is focused on effects of a single part of the pollution mixture, fine particles.
3. That it implies that air pollution is the sole cause of death.

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[5] http://www.eclaire-fp7.eu

[6] Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., et al. 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet, 380: 2224-60.

[7] World Health Organization (2014) Burden of disease from the joint effects of Household and Ambient Air Pollution for 2012. http://www.who.int/phe/health_topics/outdoorair/databases/FINAL_HAP_AAP_BoD_24March2014.pdf?ua=1

[8] The two do not add to the 7 million total, as the total recognizes that some deaths will be double counted and makes appropriate adjustment.

[9] http://www.healtheffects.org

[10] REVIHAAP (2013) Review of evidence on health aspects of air pollution – REVIHAAP project: technical report. Copenhagen, WHO Regional Office for Europe (http://www.euro.who.int/__data/assets/pdf_file/0004/193108/REVIHAAP-Final-technical-report.pdf

[11] HRAPIE (2013) Health risks of air pollution in Europe – HRAPIE project Recommendations for concentration–response functions for cost–benefit analysis of particulate matter, ozone and nitrogen dioxide. Copenhagen, WHO Regional Office for Europe. http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/health-risks-of-air-pollution-in-europe-hrapie-project-recommendations-for-concentrationresponse-functions-for-costbenefit-analysis-of-particulate-matter,-ozone-and-nitrogen-dioxide.

These are addressed below.

The focus on epidemiological evidence for quantification

With respect to the focus on epidemiology, such studies simply demonstrate the strength of association between two variables. In isolation, epidemiological association is not proof of causality, which is more accurately assessed using toxicology to explore the mechanisms of action. There are numerous examples of closely correlated variables that clearly have no relationship with each other. However, in some cases, for which the quantification of human health effects of air pollution provides a good example, it is necessary to rely very largely on epidemiology. Here, we have a burden to which all members of society are exposed, and therefore we need to understand the whole-population response, including those who are very young or very old, those who are in good or poor health. Fortunately, this problem has been considered in depth, particularly through development of the Bradford Hill criteria[12]. These provide a means for assessing when the weight of epidemiological evidence is sufficient for causality to be inferred. The criteria include the strength, consistency, specificity, plausibility, etc. of association. Various expert groups have considered these issues for air pollution and reached the same conclusion: that the weight of evidence is strong enough for causality to be accepted, and to enable quantification. As time goes on, this position is increasingly backed up by mechanistic evidence.

The reliance on epidemiology for the quantification provided by Larsen is therefore not considered at all problematic.

Attribution of impacts to fine particles

Attribution of impacts to fine particles is more problematic because air pollution is a mixture, including other pollutants such as ozone, carbon monoxide, sulphur dioxide and nitrogen dioxide and various toxic micropollutants such as lead and dioxins. Separating out the effect of one component of this mixture is at best difficult.

The HRAPIE study of WHO-Europe includes response functions for ozone and NO_2 also. Both could generate significant additional health burdens that were not quantified for Global Burden of Disease. In the case of ozone, there are questions around the use of a threshold, and around the possible existence of effects of long-term exposure, drawing on work particularly by Jerrett et al (2009a, b)[13]. Quantification by Holland (2014)[14] indicates that these ozone impacts may add 20% or more to the total damage quantified in European policy assessments for fine particles. NO_2 may cause greater impacts still, perhaps of a

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[12] Hill, Austin Bradford (1965). "The Environment and Disease: Association or Causation?". Proceedings of the Royal Society of Medicine 58 (5): 295–300.

[13] Jerrett M et al. (2009a). Long-term ozone exposure and mortality. New England Journal of Medicine, 360(11):1085–1095.
Jerrett M et al. (2009b). A cohort study of traffic-related air pollution and mortality in Toronto, Ontario, Canada. Environmental Health Perspectives, 117(5):772–777.

[14] Holland, M (2014) Cost-benefit Analysis of Final Policy Scenarios for the EU Clean Air Package Version 2, Corresponding to IIASA TSAP Report 11, Version 2a. http://ec.europa.eu/environment/archives/air/pdf/TSAP%20CBA.pdf.

similar magnitude to fine particles, though there are outstanding questions about the implementation of the response functions recommended by HRAPIE, especially with respect to the modelling of exposure.

There is very little interest in the epidemiology literature on the effects of carbon monoxide, CO, and sulphur dioxide, SO_2. With respect to CO it appears to be considered that the mechanism of action for CO is well understood, and it is concluded by toxicologists that ambient exposures are unlikely to be high enough to cause anyone to pass a threshold where effects influence bodily function. However, this can be countered by consideration of exposures from other sources, and consideration of the variable state of health across the population. With respect to SO_2, concentrations in European and North American countries where most of the epidemiology has been performed are now considered so low as not to be of much interest. However, this leaves aside the fact that concentrations in some parts of the world (including parts of Europe, such as various Balkan States) remain high.

There are then the effects of the toxic micropollutants, including toxic metals and dioxins. Some of these pollutants will be bound onto fine particles during emission, and hence their impacts on health may be captured as part of the impacts reported for $PM_{2.5}$.

It is thus possible that the analysis presented by Larsen is biased to underestimation of air pollution impacts through the emission of ozone, CO, NO_2 and SO_2, and possibly also the trace pollutants.

Which particles?

Fine particles are not a distinct chemical species, but a mixture of various organic and inorganic substances, including both ‘primary’ and ‘secondary’ particles. Primary particles are emitted directly into the atmosphere, whilst secondary particles form through chemical reactions in the atmosphere.

The convention in health impact assessment, following the recommendations of the REVIHAAP and HRAPIE studies and numerous expert groups over the years, including those advising USEPA, is to treat all types of particle as equally aggressive, irrespective of their chemical and physical properties. Logic suggests that this assumption is incorrect to some degree, but, given the consistency seen in reported effects per unit exposure to simple particle measurements (as $PM_{2.5}$ or PM_{10}) from studies at different times in different places, not so wrong as to invalidate the analysis. Whilst further research could provide insight to which particles are most aggressive to health and hence which to target to optimise policy response, the complexity of the particle mix and broader pollution environment has so far prevented progress. It is not clear, however, that this is a major barrier to efficient policy development – particles generally appear to be harmful to health – so whilst more detail on this point could fine tune analysis to inform policy development it seems unlikely to change it radically.

Air pollution as the cause of death

The third issue identified at the start of section 0, the inference that air pollution is the sole cause of death has consequences both for understanding the nature of the burden to health and for economic valuation. Rabl et al[15] underline the point that reducing air pollution (or, come to that, any burden on health) will not ultimately reduce the number of deaths, but will increase longevity.

One can envisage three alternative roles for air pollution in relation to mortality:

1. As the primary cause of death.
2. As one of a number of factors that affect longevity through collective impacts on the cardiovascular or respiratory systems.
3. As a final trigger for mortality, when other disease is well advanced.

Hence, air pollution could be one of a number of factors that predispose one to dying at an earlier age than that at which one may be considered biologically programmed to attain. Other relevant factors include the effects of diet and obesity, smoking, exposure to communicable disease and so on. Individually, each burden might not be considered severe enough to be 'the cause of death', but they will each have some role in determining when (e.g.) cardiovascular disease becomes sufficiently bad enough that the subject dies. An exception concerns the development of cancer through exposure to air pollution of some sort[16], where the quantified excess of cancers can be attributed to pollution. However, these deaths only account for a small part (less than 10%) of the total disease burden of air pollution according to the estimates provided above.

This issue has received rather scant attention in the literature. However, it has been considered by COMEAP, the Committee on the Medical Effects of Air Pollutants reporting to the UK Department for Health[17]. The view taken by COMEAP was that the mortality response function for particles was best applied to estimate the loss of life expectancy across the population, but could also generate an estimate of 'equivalent deaths':

> *"The current (2008) burden of anthropogenic particulate matter air pollution is, with some simplifying assumptions, an effect on mortality in 2008 equivalent to nearly 29,000 deaths in the UK at typical ages and an associated loss of total population life of 340,000 life-years. The burden can also be represented as a loss of life expectancy from birth of approximately six months."*

They continue by saying that:

> "*It is not known how this population-wide burden is spread across individuals in the population, but we can speculate between various possibilities. Our results are*

[15] Rabl, A., Spadaro, J. and Holland, M. (2014) How Much Is Clean Air Worth? Cambridge University Press.
[16] IARC (2014) Air Pollution and Cancer. http://www.iarc.fr/en/publications/books/sp161/index.php.
[17] COMEAP (2010) The Mortality Effects of Long Term Exposure to Particulate Air Pollution in the United Kingdom. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/304641/COMEAP_mortality_effects_of_long_term_exposure.pdf.

consistent with an average loss of life ranging at one extreme from 11.5 years if air pollution was solely responsible for 29,000 deaths to, at the other extreme, six months if the timing of all deaths was influenced by air pollution. We believe both of these extremes to be extremely unlikely. Given that much of the impact of air pollution on mortality is linked with cardiovascular deaths, it is more reasonable to consider that air pollution may have made some contribution to the earlier deaths of up to 200,000 people in 2008, with an average loss of life of about two years per death affected, though that actual amount would vary between individuals. However, this assumption remains speculative."

At one level this may be thought of as highlighting significant uncertainty in the estimates of mortality made by various authors. However, whilst it questions the nature of the impact on mortality, it reinforces the message that air pollution has a significant impact on health.

The questions raised in this section are of particular relevance to the valuation of mortality effects, whether in monetary terms for cost benefit analysis of pollution abatement options, or for comparative purposes as in Chapter 2 of Larsen's Assessment Paper where it is stated that the 6 or 7 million deaths attributed to air pollution is about four times higher than for child and maternal under-nutrition. If we regard all estimated deaths as being equal this is a valid comparison. However, does this make sense if child and maternal mortality accounts for a much higher quantity of lost life expectancy?

Morbidity and non-health impacts

Global Burden of Disease and the Larsen paper focus particularly on mortality impacts of air pollution, for two reasons, the availability of response and incidence data at a global level and the natural importance of mortality. However, for mortality to occur it is natural that there will also be some increase in morbidity. This takes various forms, with the WHO HRAPIE study recommending quantification of various effects, including:

- Hospital admissions for respiratory and cardiovascular illness
- Bronchitis in both adults and children
- Exacerbation of asthma
- Minor effects leading to restrictions on activity, including the ability to work

Further effects can be added to this list. One example is the morbidity effects associated with cancers., another the development of long term cardiovascular disease and stroke. An example of perhaps only historical importance in Europe and the USA, but possibly greater importance in developing countries as a consequence of higher pollution levels and worse diet is the development of rickets in children.

This underlying disease clearly adds to the health burdens described through estimated mortality. It adds to the health burden in another way also, through the demands placed on healthcare systems. Further to this, it adds costs to business through increased sickness amongst workers. Analysis for the European Commission[14] indicates that these benefits can be substantial.

Benefits of clean air policies are substantially broader than those relating to mortality and morbidity. Larsen recognises the non-health benefits of improved stoves for reducing household air pollution, in terms of reduced fuel costs and time spent collecting fuel, in the case of biomass. Section 0 highlighted impacts on ecosystems and building materials including cultural heritage.

Control options

Larsen considers four options for emission controls:

1. Removal of energy subsidies
2. Taxation to influence demand and internalise externalities
3. Fuel quality improvement
4. Technological improvements, including legislation requiring end of pipe abatement

With respect to energy subsidies it is noted that most are applied to petroleum products, placing renewables and other less polluting alternatives at a disadvantage. On taxation, it is noted that some actions, for example differential taxation of leaded gasoline, has been very successful. However, there are some tax policies that provide the wrong signal to consumers: in most countries diesel vehicles are given preferential treatment over those using gasoline, although the health impacts of diesel through air pollution are increasingly recognised as a major threat to health[18]. Amongst OECD Member States, only Switzerland, the UK and the USA tax diesel vehicles more than those running on gasoline.

Larsen acknowledges that some options are not considered in his paper. A notable omission is the use of emission ceilings, adopted most famously through the Kyoto Protocol on greenhouse gases, but also through legislation under the UNECE (United Nations Economic Commission for Europe) Convention on Long Range Transboundary Air Pollution[19]. These ceilings provide a flexible mechanism by which countries, or certain industries within a country, can decide themselves on the most appropriate route for emissions control.

Another subject of relevance here is climate mitigation actions. Given that CO_2 and most of the air pollutants of concern here share a common main source, fossil fuel combustion, many actions to reduce CO_2 will also reduce PM, CO, NOx and SO_2 emissions. This issue is discussed further below, in Section 0.

Larsen notes that the non-linearities in the PM response function are significant over the range of concentrations seen in many (particularly Asian) cities. Therefore, to gain the

[18] OECD (2014) The cost of air pollution: Health impacts of road transport. http://www.oecd.org/environment/cost-of-air-pollution.htm

[19] Reis S., Grennfelt P., Klimont Z., Amann M., ApSimon H., Hettelingh J-P, Holland M., LeGall A-C, Maas R, Posch M, Spranger T, Sutton MA and Williams M. 2012. From Acid Rain to Climate Change. Science 338.

same magnitude of benefit requires a bigger reduction in exposure than in cities where concentrations are lower. However, the reason that exposures are lower in (for example) most of Europe and North America, is that these regions have considered it appropriate to dedicate significant resource to the problem already. The good news is that for the more polluted regions, substantial reductions in exposure can be made at relatively little cost through the adoption of basic pollution control measures. For outdoor (ambient) air pollution these include correct maintenance of boilers and other equipment, the use of high efficiency particle filters, and switching to less polluting fuels (e.g. low sulphur coal, natural gas, or renewables). Household air pollution can be greatly reduced by improving stoves and fuels and ensuring that combustion gases are vented to the external atmosphere, reducing the exposure of those inside the buildings. Some of these measures will, overall, reduce costs to users, for example through fuel saving or increased service life for equipment.

Benefit-cost ratios

For household air pollution, the benefits of switching to improved stoves are estimated by Larsen to outweigh costs by a factor of between 7 and 41, depending on region. Roughly two thirds of benefits are related to health (mortality) impacts and one third to fuel cost and time savings. The added benefits of switching to less polluting LPG as a fuel, in preference to biomass or coal have a lower benefit-cost ratio of from 1.2 to 3.9, again depending on region.

Larsen's Table 5.5 provides estimates of the benefit of reducing $PM_{2.5}$ emissions by 1 tonne in the different regions of the world, accounting also for variation in pollutant concentration. It should be noted that these results are specific to ground level sources, and hence have less relevance to industrial emissions, which in some countries, such as China, make an important, perhaps dominant, contribution to exposure. The Table also focuses on primary $PM_{2.5}$: to gain a full understanding of the problem and of the costs and benefits of different control strategies it is also necessary to understand the contribution of secondary aerosols formed as reaction products in the atmosphere following release of precursors such as SO_2, NOx, ammonia and volatile organics. Analysis of the contribution of these precursors has been carried out in numerous policy analyses, for the European Commission, USEPA, in China and many other countries. Damage per tonne estimates are available at least in some regions[20] .

The relevance of air quality limit values

Air quality limit values do not for the most part infer total protection of the population. Research in Canada[21] for example, has demonstrated effects of fine particles down to very low concentrations (less than the WHO guideline of 10 µg/m^3).

[20] E.g. European Environment Agency (2014) Costs of air pollution from European industrial facilities 2008-2012. file:///Users/Mike/Downloads/costs-of-air-pollution-from-european-industrial-facilities.pdf.

[21] Crouse et al (2012) Risk of Nonaccidental and Cardiovascular Mortality in Relation to Long-term Exposure to Low Concentrations of Fine Particulate Matter: A Canadian National-Level Cohort Study. http://ehp.niehs.nih.gov/1104049/.

Larsen notes the tension in air quality improvement policies between the desire that no individual should be exposed to 'significant' risk (however 'significant' might be defined), and the desire to maximise the benefits of policies to society. This opens the question of whether society is best served by ensuring that a given sum of money is spent ensuring that all individuals have a minimum level of protection, or on maximising the reduction in health impact across society. From an equity perspective the former may be preferred, from an economic perspective the latter.

Discussion of limit values leads naturally to consideration of monitoring, the means of checking compliance. Money spent on monitoring can improve the effectiveness of policies by enabling better targeting on areas where the highest concentrations are likely (where equity is a key driver for targets) or the sources that cause the highest exposure (where targets are driven by total population exposure). However, money spent on monitoring is clearly money not spent on pollution control. Prior to monitoring, therefore, it is necessary to consider what can be learned from previous experience, where monitors should be located and what actions should be implemented as soon as possible without waiting for detailed information from air pollution measurement. Particularly in locations where concentrations are clearly very high and a substantial threat to health, it needs to be recognised that the more time is spent developing a better understanding the problem, the greater the health and other costs of inaction.

Larsen notes the variability of outdoor air quality targets in different countries, and also in relation to the WHO guidelines. This variability extends beyond the numbers defining the limits to location, whether limits are to apply everywhere or only in urban background locations, and whether they differentiate according to the dominant activity in defined areas (e.g. residential vs. industrial). Consideration of which limit values are strictest is thus not straightforward.

The efficient adoption of air quality limit values thus requires consideration of a number of factors:

- The ultimate goal for air quality, whether to be reached in the short or long term
- The path to meeting that ultimate goal, whether in one step or incrementally through a series of interim limit values
- The attainability of that a value over a given time period
- The type of location to which the limit applies

There may be no point in legislating for a limit value that cannot be achieved; it may act as a deterrent to any action being taken when compliance is seen as a black and white issue. Determination of the ultimate goal and an indication of the time scale over which it may be achieved enables cost-efficient plans to be adopted, reducing the potential for 'solutions' becoming redundant within their lifetime as more effective abatement measures become necessary.

Similar concerns around monitoring extend to household air pollution. Larsen is correct when concluding that the most attractive targets in this domain concern not some measurement of air quality, but targets on the types of stove and fuels being used. Again, there is sufficient evidence available to enable exposure to be estimated with reasonable accuracy once the type of stove and fuel being used are known, without undertaking a major monitoring campaign.

Additional perspectives

This chapter is focused on opportunities for increasing the efficiency of actions for improving air quality. The following are highlighted:

- The need to improve the science
- The use of cost-effectiveness analysis
- Targeting action to maximise effectiveness
- Characterisation of mortality
- Co-benefits and trade-offs with other policies
- International collaboration

The need to improve the science

There are several areas where science could be improved, for example:

- Differentiation of particles and particle sources according to the level of harm caused, as referred to above in Section 4.1.3.
- Understanding the role of some pollutants, particularly NO2.

- Clarification of the role of air pollution on mortality, as discussed in Section 0.

- Characterisation of morbidity impacts. These have received less attention than mortality, partly because they are harder to collect data for (mortality and cause of death data are routinely collected almost everywhere). Whilst mortality alone provides sufficient impact to validate the case for additional action on air pollution, the information on morbidity effects is useful in order to:

    - Provide a complete view of health impacts, and the links to other issues including obesity, smoking, low birth weight.

    - Demonstrate validation of the mortality impact: A large impact on mortality clearly needs to be underpinned by a large impact on morbidity also.

    - Provide additional perspectives, for example relating to the costs to healthcare systems and the impacts on productivity in the workplace.

- Valuation of health impacts, to clarify the role of the alternatives for mortality valuation, the value of statistical life and the value of a life year, and to better understand the relative value of different morbidity effects.

- Integration of control options with cost-effectiveness modelling designed to define optimal abatement strategies. This is discussed in more detail in the next section.

Whilst listing areas where the science could be improved, it is important to recognise that this is not a signal to delay action until better information is available. There is already sufficient information available, and consensus amongst experts, to make a robust case for extensive action on air quality improvement. Delay might appear to make some marginal improvement to the efficiency of measures when introduced, but the overall efficiency of the air quality improvement strategy falls through the costs of inaction inherent in the delay.

The use of cost-effectiveness

As already noted, cost-effectiveness analysis (CEA) is a widely used tool for identifying cost-effective solutions for pollution abatement[22]. The approach identifies measures for reducing a pollutant and then ranks these measures in terms of the marginal cost of abatement (e.g. €/tonne abated) to provide a 'cost curve'. There is potential for developing cost-curves that address several pollutants simultaneously, where some common indicator of effect is available. The best known examples have been developed for dealing with greenhouse gases, where emissions are converted to a common scale using established estimates of the global warming potential relative to CO_2.

CEA suffers the following problems:

- The list of measures is rarely complete. Some important options for emission control, such as fuel switching, energy efficiency and behavioural measures may, for various reasons, be difficult to integrate with a cost curve.

- Common indicators of effect across pollutants may not be available, or appropriate at the scale required. For example, the health impact per unit of sulphur dioxide emitted will vary depending on the location of emission (proximity to population) and the wider pollution climate (especially, the availability of other pollutants with which to react to form sulphate aerosols – one component of 'particulate matter').

- The benefits of action for reducing air pollution cannot be fully captured in a cost-curve. Transport efficiency measures, for example, will introduce a variety of additional types of benefit (physical fitness, reduced noise, congestion, etc.) that cannot be captured in common indicators of effect as described above. For this, a wider cost-benefit analysis (CBA) is necessary, where impacts of diverse types are

[22] IIASA (2014) The Final Policy Scenarios of the EU Clean Air Policy Package. Version 1.1a, http://www.iiasa.ac.at/web/home/research/researchPrograms/MitigationofAirPollutionandGreenhousegases/TSAP-final-report.en.html.

converted to a monetary equivalent. The use of CBA has the added benefit of defining how far it is appropriate to reduce emissions using the set of measures defined in the cost curve, by identifying the point at which marginal costs and benefits are equal.

CEA is certainly a vital tool for rational policy evaluation in providing a first indication of priority measures. However, its limitations must be recognised in order to select the most optimal policies.

Targeting action: which pollutants to prioritise?

The pollutants of most public concern are not necessarily those that cause the greatest damage. For example, the estimated damage per kg of dioxin emission is very high, but dioxins are emitted in very small quantities from modern facilities, sufficiently so that emissions of other pollutants (e.g. particles, NOx and SO_2) cause far more damage in total, according to the best available estimates. Much of the concern around emissions of dioxins and toxic metals has focused on waste incineration. Unfortunately, much public comment about waste management fails to recognise the improvements that have been made to incineration technologies over recent decades, and the development of more efficient energy utilisation technologies through combined heat and power. It also fails to recognise related benefits from other environmental protection actions, such as action to reduce the amount of lead, mercury, cadmium and other toxic substances entering products, and hence eventually the waste stream also. To imply that the harm associated with modern incineration technologies is little different to that caused by old fashioned facilities distorts an important debate.

The conclusion here is that the focus of action needs to be on the emissions that cause the greatest harm, not necessarily those that cause the greatest public concern at any time.

Targeting action: which facilities to prioritise?

Analysis by the European Environment Agency highlights the fact that most air pollution damage from industry is caused by a small number of facilities (Figure 4)[23]. Of over 10,000 facilities covered by the European Pollutant Release and Transfer Register (E-PRTR), 50% of damage is linked to emissions from only 147 plant (1% of the total). Such analysis helps target future emission controls. The same principles can be applied to other sources, to highlight the most damaging types of vehicles, etc.

Some caution is necessary in interpretation of the results of Figure 4:

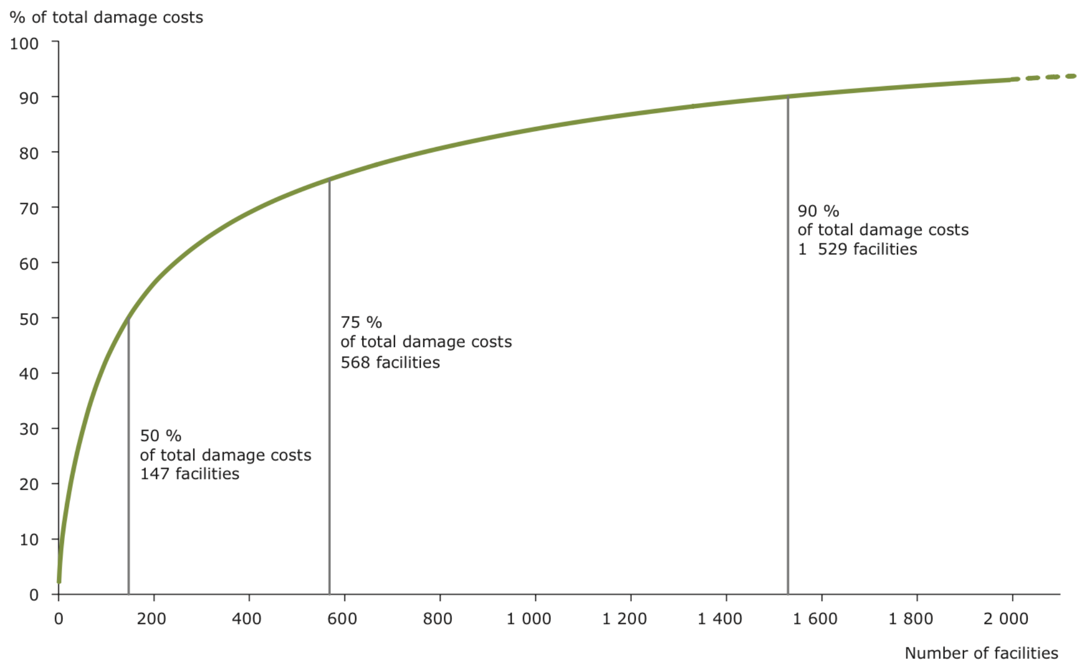
- It is specific to industrial facilities in Europe, and largely the European Union. In other parts of the world the same bias to a few large facilities may not apply to the same degree.
- The figure takes no account of the efficiency of plant as E-PRTR includes no data on output to compare with emissions. It is thus possible that a very large plant subject to

[23] European Environment Agency (2014) Costs of air pollution from European industrial facilities 2008-2012. file:///Users/Mike/Downloads/costs-of-air-pollution-from-european-industrial-facilities.pdf.

a high level of environmental regulation would be less polluting per unit of output than a number of smaller plants.

Accepting these caveats, Figure 4 still demonstrates the potential for prioritisation of environmental protection measures, targeting action on the most polluting sources.

Figure 4. Cumulative air pollution damage to health from industrial facilities reporting to the European Pollutant Release and Transfer Register (E-PRTR).



How best to characterise mortality?

This section continues the debate started in Section 0. Opinions are divided as to whether mortality associated with air pollution should be valued against the number of deaths using the value of statistical life (VSL) or against the loss of life expectancy using the value of a life year (VOLY). Of the two, the VSL is by far the better established, an authoritative review of available values being provided by OECD[24]. Evidence that the VSL does not decline with age to any appreciable degree is cited as evidence against the validity of valuation in terms of life expectancy. However, the economic debate about the validity of the two approaches for mortality valuation overlooks the fact that action on air pollution cannot stop people from dying – all it can do is affect longevity by delaying the timing of death. From this perspective, what is relevant is the period spent alive, rather than 'death' as such. It also overlooks the fact that air pollution is typically not the sole causal agent affecting mortality. Air pollution will affect deaths from cardiovascular causes, but so will other factors, such as poor diet and lack of exercise. Efficient allocation of resource to address the problems of cardiovascular disease is clearly better defined through

[24] OECD (2012) Mortality Risk Valuation in Environment, Health and Transport Policies. OECD, Paris.

consideration of the relative impacts of each contributory factor, and this cannot be done purely through quantification of impact in term of death.

Fortunately, available evidence suggests that the choice of VSL or VOLY for mortality valuation is not a major 'game changer'. Analysis for the European Commission indicates that the VSL/VOLY choice makes around a factor 2 difference to the total estimate of monetary value of damage[14]. However, this does not lead to a factor 2 difference in the level of abatement considered appropriate according to CBA. Again, the analysis for the European Commission (IIASA, 2013) shows that the shape of the marginal abatement cost curve largely dictates the point at which marginal costs and benefits are equal. The factor 2 difference in the benefits of action translates to only around a 5% difference in ambition level for its Clean Air Policy Package.

Co-benefits and trade-offs with other policies

It is important to recognise the linkages present between pollutants, and with other environmental concerns. Within the European Union, controls on industry take the approach of integrated pollution prevention and control, recognising the cross-media tensions that can exist: end of pipe controls to prevent the release of air pollution will generate other solid or liquid waste streams that need to be controlled. Without proper coordination of activities it is possible to generate significant dis-benefits for society.

However, the clearest links to air pollution are with climate change. The major air pollutants (fine particles, NOx and SO_2) and greenhouse gases (CO_2, N_2O, CH_4) are associated in large part with combustion and energy systems. There is, however, some reluctance in policy circles to make these connections, with the effect of reducing the economic efficiency of controls. Perhaps reaching agreement in one area is hard enough without broadening the scope of action to a range of environmental issues. However, the need for 'joined up' action is clear as the following examples show: end-of-pipe abatement of air pollutants generally involves some energy/GHG penalty, whilst the use of biomass for combustion to mitigate carbon emissions can generate significant emissions of fine particles and toxic trace pollutants in the form of PAHs.

The extent of interactions between air pollution, climate and other burdens on society has been highlighted in a study for the UK's Climate Change Committee, a body funded by government but at arms length from it[25].

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[25] A series of studies are available on the website of the UK's Climate Change Committee to report evaluation of its 4th Carbon Budget for the UK (http://www.theccc.org.uk/publication/fourth-carbon-budget-review/). The main report on cobenefits is by Forster et al (2013) Review of the impacts of carbon budget measures on human health and the environment. http://www.theccc.org.uk/wp-content/uploads/2013/12/AEA-Review-of-the-impacts-of-carbon-budget-measures-on-human-health-and-the-environment.pdf. Data sheets for the report are available at http://www.theccc.org.uk/wp-content/uploads/2013/12/Health-Env-accounting-framework.zip, and further information on air quality assessment by ApSimon and Oxley is available at http://www.theccc.org.uk/wp-content/uploads/2013/12/Air-quality-impacts-of-potential-CCC-scenarios.pdf.

International collaboration

Concern over air pollution was over many centuries considered a local, generally city-scale issue. The response to the Great London Smog of 1952 and similar events in cities elsewhere was to move sources of pollution away from urban areas and to erect very tall chimneys for power plants and other major combustion facilities (so-called 'dilute and disperse' policies). During the 1960s and 1970s the problem of 'acid rain', whereby pollution impacts were noted on ecosystems far removed from centres of human activity were identified, establishing air pollution as a regional/continental problem. It is now increasingly recognised that this, too, is insufficient, with air pollution impacts effective at the hemispheric scale, particularly in relation to ozone.

Politically, this creates difficulty because the most efficient policies in most areas will require international cooperation. However, a model for this exists already through the UN Economic Commission for Europe's Convention on Long Range Transboundary Air Pollution and related activities of the European Commission. The resulting international cooperation on research and analysis has paved the way for more efficient approaches to dealing with air pollution than would otherwise be available[19].

Conclusions

The main conclusions of this work are as follows:

1. The effects of air pollution on health are substantial, with ambient air pollution and household air pollution together responsible for a significant share of the global environmental burden of disease.

2. Cost efficient solutions for reducing pollutant emissions are available. For developing countries, the experience of the countries of western Europe and North America can be particularly informative in relation to identification of the measures that work best and at least cost to reduce emissions of air pollutants. These experiences can also be useful for highlighting bad practice, what development paths should not be followed in the interests of protecting public health. A good example of this is the increased dieselisation of the vehicle fleet seen in many countries.

3. An extensive research agenda can be compiled for improving knowledge on air pollution effects and control measures. However, this should not be taken as a sign that knowledge in this field is generally lacking, or that governments should wait to take action. Delay in action confers a 'cost of inaction'. Most cost-efficient actions will remain cost efficient irrespective of the conclusions of further research. The costs of the research needed for further optimising response strategies will be a small fraction of the costs of remaining impacts and the costs of abatement.

4. Finally, it is essential to emphasise the need for 'joined-up policy making' with other policy areas. In particular, a failure to link climate and air pollution policies will incur significant penalties, both in terms of cost and unnecessary impacts to health, ecosystems and the built environment. Further efficiencies can be gained through international collaboration.

This paper was written by Mike Holland Independent, Consultant, Ecometrics Research and Consulting. The project brings together 60 teams of economists with NGOs, international agencies and businesses to identify the targets with the greatest benefit-to-cost ratio for the UN's post-2015 development goals.

For more information visit post2015consensus.com

COPENHAGEN CONSENSUS CENTER

Copenhagen Consensus Center is a think tank that investigates and publishes the best policies and investment opportunities based on how much social good (measured in dollars, but also incorporating e.g. welfare, health and environmental protection) for every dollar spent. The Copenhagen Consensus was conceived to address a fundamental, but overlooked topic in international development: In a world with limited budgets and attention spans, we need to find effective ways to do the most good for the most people. The Copenhagen Consensus works with 100+ of the world's top economists including 7 Nobel Laureates to prioritize solutions to the world's biggest problems, on the basis of data and cost-benefit analysis.

Post-2015 Consensus: Air Pollution Perspective, Holland[1]

Addendum, April 2015-04-27
Dr Mike Holland, mike.holland@emrc.co.uk

Summary

The benefit cost ratios for targets on outdoor air pollution estimated by Larsen, in the region of 0.3, are derived from an extremely limited analysis of abatement options, that are neither the most cost-effective nor the most efficient for reducing population exposure. The approach taken to valuation of health impacts does not reflect practice elsewhere, indeed, the valuations adopted appear to be inconsistent with Larsen's own analysis. Putting the costs and benefits together, air pollution policies have been subject to repeated cost-benefit analysis in many parts of the world, showing high benefit:cost ratios (BCRs) for air pollution improvement, completely different to those provided by Larsen. This needs to be reflected in any publication, for example online or by Cambridge University Press.

This raises serious questions about the quality of outputs from the Copenhagen Consensus programme generally, and then its reliance on the BCRs generated by the papers, for example, through the "Paper Authors' Ranking" exercise launched in April 2015.

Introduction

My Perspective Paper for the Copenhagen Consensus series was written to reflect on the paper by Larsen[2] and to add further perspectives, as appropriate. Delays in the production of the Larsen paper, however, meant that I did not have access to the final version, in particular, the section on the costs and benefits of action to reduce outdoor air pollution. Having now had the opportunity to read it, I find that the conclusions reached on the BCRs for outdoor air pollution targets do not reflect detailed analysis undertaken elsewhere. The text that follows is not intended as a comprehensive overview, but an instant reaction on the Larsen BCR result for outdoor air.

[1] http://www.copenhagenconsensus.com/publication/post-2015-consensus-air-pollution-perspective-holland
[2] http://www.copenhagenconsensus.com/publication/post-2015-consensus-air-pollution-assessment-larsen

Larsen's abatement cost analysis

Larsen states that:
This paper cannot hope to assess the cost of $PM_{2.5}$ abatement from all these diverse sources. Two policy dimensions of abatement are briefly discussed: (i) energy subsidies; and (ii) taxation policies. This is followed by estimates of cost of abatement from four sources of $PM_{2.5}$: (i) household use of solid fuels for cooking and heating; (ii) solid waste management; (iii) fuel quality; and (iv) road vehicle technologies.

Larsen recognises that exposure to fine particles arises not only through exposure to particles emitted directly to the atmosphere, but also through exposure to particles formed in the atmosphere from emissions of other pollutants such as SO_2, NOx and NH_3. However, these other pollutants are not addressed at all through his costed abatement options. The focus on household and transport emissions also excludes emissions from notable sources such as industry and agriculture.

Larsen's results for outdoor air are illogical, in that the tighter limits have a higher BCR (0.4) than the most relaxed target of 35 ug/m^3 (0.3). This is presumably through reliance in his analysis on a small set of control options.

Availability of options

A number of options that are <u>not</u> accounted for in Larsen's analysis will save money, for example:

- Improved energy (etc.) efficiency through the use of better appliances
- Improved energy (etc.) efficiency through system design
- Improved maintenance of combustion equipment
- Abolish subsidies (promoting efficiency and reduced waste more generally).

The scope for these measures should not be underestimated, particularly in regions where subsidies and other disincentives to efficiency exist.

Once these and other cost saving measures have been implemented there are many other low cost options. This is highlighted in the following figure, used in the development of the European Commission's Clean Air Policy Package of December 2013[3]. The figure shows that in the EU, a group of countries that have been subject to a large amount of air quality legislation since the 1950s, there are still, in 2013, measures available where benefits exceed costs – covering more than 75% of the available 'technical' improvement. The marginal benefits of controls at the 50% gap closure level show a BCR between about 4 and 25. This

[3] http://ec.europa.eu/environment/air/clean_air_policy.htm

is after many other measures, for example improved fuel quality, high efficiency particle collectors, flue gas desulphurisation and so on have been implemented (all of which have previously been adopted following extensive use of cost-effectiveness and cost-benefit analysis).

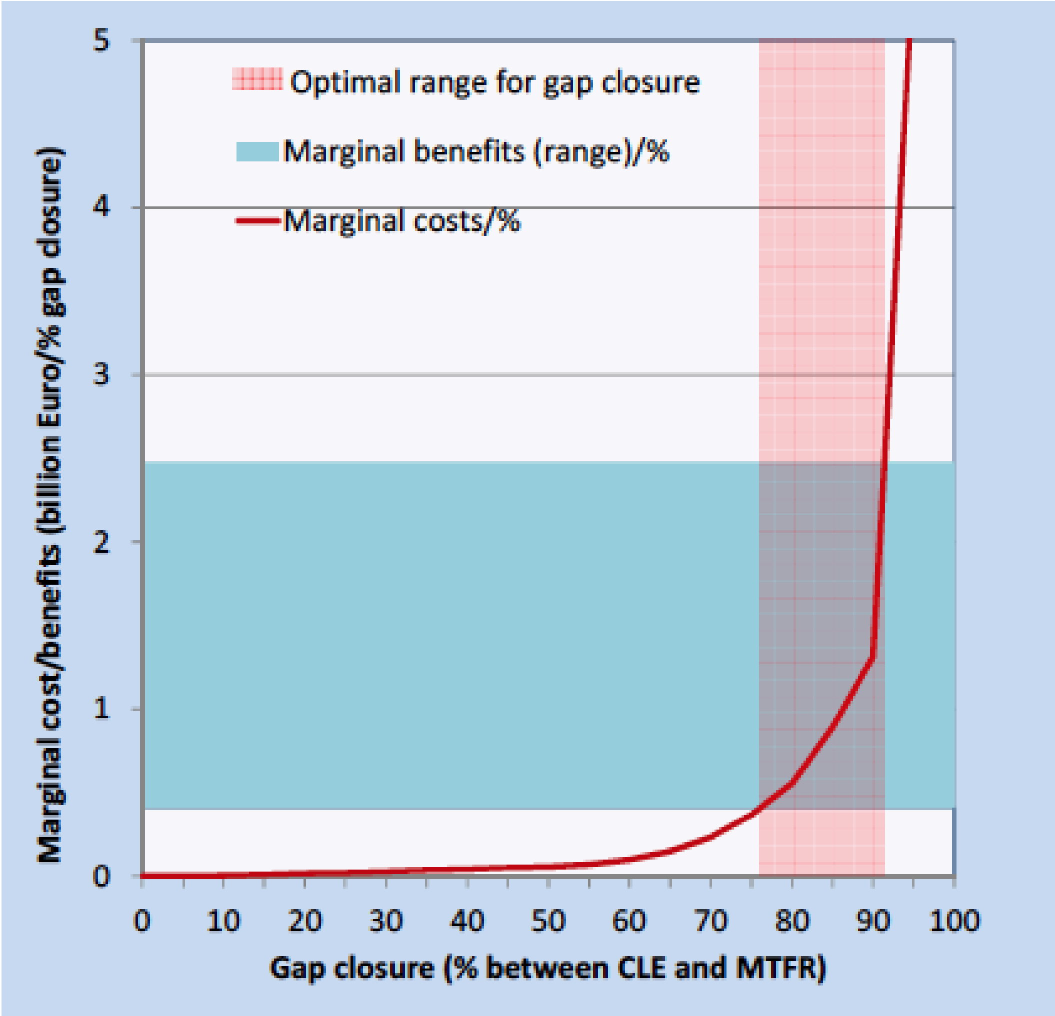

Figure 4.2: Marginal emission control costs and marginal health benefits in 2025

Note to the figure: The x-axis shows progression from emissions under current legislation in 2025 (CLE) to reduced emissions under a scenario of 'Maximum Technically Feasible Reduction' – bringing in all of the abatement measures contained in the GAINS model[4] run by IIASA (the International Institute of Applied Systems Analysis). The range of marginal benefits (blue band) shows the effects of different assumptions on mortality valuation.

Beyond this, there are further non-technical measures, not considered in the modelling that was done for the European Commission, that could have a major impact on air quality, including congestion charging and other taxation policies and fuel switching.

[4] http://gains.iiasa.ac.at/models/

Valuation of health benefits

Larsen calculates a value of a statistical life year (VSLY) by dividing the value of statistical life (VSL) by the number of years lost prematurely to air pollution, for the latter using estimates from Global Burden of Disease. Larsen states that:
VSL can be converted to a value of statistical life year (VSLY) by dividing VSL by the number of years prematurely lost to death. VSLYs are thus in the range of US$1.2–224 thousand. By the second measure, a uniform value of US$1,000 and US$5,000 per year of life lost (YLL) is applied. The VSLYs are within this range for the lowest income regions of the world, but are much higher for middle and high income regions.

The calculation of VSLY by dividing VSL by life years lost contradicts the VSL literature, as it implies a dependency of valuation with age that is not observed empirically.

In any case, the subsequent adoption of the range of $1,000 to 5,000 ignores this calculation. It is quite unclear why a uniform range has been adopted, and then why it is so low, a range that covers only Sub-Saharan Africa and limited parts of Asia.

In summary, the methods adopted for valuation of health impacts do not reflect current practice and seem artificially low.

Paper Authors' Ranking Exercise

The ranking exercise is structured as follows:

The Millennium Development Goals were concise, effective and galvanised support around 18 smart targets. The UN is on track to choose 169 targets. 169 priorities is as good as zero priorities.

If you were deciding which targets the world should focus on to 2030, which would you choose?

Rate the following targets into one of five categories.

EXCELLENT: Benefit for every dollar spent $15+
GOOD: Benefit for every dollar spent $5-$15
FAIR: Benefit for every dollar spent $1-$5
POOR: Benefit for every dollar spent <$1 or the target is poorly specified
UNCERTAIN: Evidence is unclear
For each target below the median benefit-cost ratio is provided from the paper. Click on the topic and target links for more information.

	Excellent	Good	Fair	Poor	Uncertain
Trade Reduce world trade restrictions (full Doha), $2011					
Trade Freer regional Asia Pacific Trade, $1300					
Gender Ensure womens' rights to own and inherit, Likely high					
Gender Increase women's political representation, Likely high					
Gender Increase women's economic opportunities, $7					
Gender Increase girls' years of schooling by 2 years, $5					
Gender Reduce child marriages, Likely to be low					
Illicit Financial Flows Make beneficial ownership info public, $49					
…					
Air pollution Better cookstoves to cut indoor air pollution, $10					
Air pollution Cut outdoor air pollution globally, $0.3					
…					

It is unclear what level of input is required to complete this exercise. On the one hand, a respondent could simply take the results as given. Hence, the two trade options at the head of the list would be rated excellent, the first two gender issues as excellent or good, the next two as good, and a reduction in child marriages as poor. This adds nothing to the list as it stands, with BCRs as stated.

At the other extreme a respondent could, in theory, read all of the papers and reach his or her own conclusions about the quality of work and representativeness of the BCR results given. However, given the number and diversity of the targets listed this is impractical. Even if it were possible, there is no provision for highlighting which respondents have gone through the exercise in huge detail, and which have simply taken the results as given.

Taking one specific example, on the basis of the results given in the table, outdoor air pollution would be rated poor by almost all respondents, but (as noted above) this is on the basis of a very limited analysis that conflicts with the results of a large literature based on detailed policy analysis in many countries around the world. Experts in trade, gender, finance, etc. cannot be expected to know this.

I fully share the objectives of the overall programme, to focus effort on goals likely to bring the greatest benefit. However, I think that this simplistic survey could only serve to undermine the work of the Copenhagen Consensus.

Post-2015 Consensus: Air Pollution Perspective

Reply by Bjorn Larsen

The main issues that relates to Holland's comments are around i) valuation of health effects; ii) choice of abatement options assessed; and iii) cost of abatement.

Health effects are valued using three measures: 1) VSL; 2) DALY=US$1000 and 3) DALY=5000. The VSL is based on meta-analyses of CV studies done for the OECD. The VSL for Western Europe is US$ 1.9 million in 2012. This translates to a benefit per ton of PM2.5 reductions of US$ 321700, reflecting an intake fraction of 45 ppm for ground level distributed PM2.5 sources.

Abatement costs of some road transport sector and solid waste management options are estimated to about US$ 15000-20000 per ton of PM2.5, and US$ 3000-14000 for curbing pollution from solid fuels used for cooking in urban areas (especially in Asia).

So if abatement costs are US$ 15000-20000 per ton of PM2.5 in Western Europe, the benefit-cost ratios (BCRs) would be on the order of 15-20. This is quite consistent with much of the modelling work in the EU, of which Holland has been much a part of.

In low and middle income (LMI) countries, the VSL is much smaller (unitary income elasticity), while most of the abatement options assessed in the paper is constant across regions (except solid waste management options; controlling the use of solid fuels for cooking in urban areas). Thus the BCRs are proportionately smaller, but mostly larger than one when benefits are valued using VSL.

These results seem quite consistent with what has been found in other studies around the world, contrary to Holland's assertion. When applying DALY=US$ 1000 to 5000, the BCRs are of course very much smaller and very different than the BCR when using VSL.

The results that the BCRs can be higher at tighter limits of PM2.5 concentrations are not illogical at all. Marginal benefits of PM2.5 abatement are in fact higher at lower PM2.5 concentrations because the concentration-response function is strictly concave as applied in the GBD 2010 project, consistent with evidence reported by for instance Pope et al in the last decade. So the BCRs depend on the relative slope of the MB vs MC curves. This is illustrated in a recent paper by Pope et al 2015, including reputable economist Maureen Cropper, in the J. of Air Waste Management Ass.

A major limitation of the paper is its inability to provide a CBA and abatement costs of all major PM2.5 control options. This would simply be impossible, given the diversity across countries and regions, and even within a country and a city. Therefore the focus was on ground level distributed PM2.5 for which estimate of intake fractions are available for several cities in most countries of the world, and thus for which abatement benefits per ton can be estimated. Unit benefits of large point sources or areawide sources (e.g., agriculture) vary tremendously across locations and estimation requires a far more detailed analysis than the time permitted for this paper. This type of work has been done in the EU and other high income regions but rarely in LMI countries (some done in China for instance), and the focus of the paper was on LMI countries where the vast majority of deaths from PM2.5 occur.

Holland lists some abatement options with negative marginal cost, such as some energy efficiency improvements and good housekeeping measures. Beyond these, it would be useful if Holland can provide some figures on PM2.5

abatement costs in the EU and other parts of the world. The modelling papers on the EU do not seem to present abatement costs per ton of PM2.5. This might be for good reasons if the abatement modelling is simultaneously of multiple pollutants, making it difficult to apportion costs to each pollutant. But, even figures with full cost allocation to PM2.5 would be helpful.