reduction to this pre-set list[12]. This is unfortunate, as a zealous effort to eliminate phantom reductions from the list can also limit states' opportunities to innovate. It is critical for decision-makers to be aware of cost-effective, scalable and verifiable behaviour-based programmes when these decisions are made. Behavioural scientists can assist in filling knowledge gaps by synthesizing results from rigorous evaluations of behavioural programmes that are candidates for inclusion in compliance plans. Research by industry and academia is rarely integrated into more robust meta-analyses, but substantial insights could be gained if it were.

Research agenda

If the final rule is friendly towards the inclusion of programmes engaging behavioural science, and if states respond by including robust demand-reduction efforts in compliance plans, much research will be needed to expand the current knowledge base. States should be encouraged to follow the lead of the Northeast Energy Efficiency Partnership, which has provided a forum for public utility commissioners and air-quality regulators to act collectively to share research results and reduce the costs of EM&V and other 111(d) compliance issues.

Behavioural scientists should include as research targets metrics of success that are relevant to EM&V requirements, once such metrics are defined. Collaborations with industry, a coordinated research agenda within the scientific community, and the establishment of 'best practices' guidelines for researchers can ensure a more streamlined transition from research into practice.

Much of the success of the rule will be determined by the decisions of federal and state regulators in the months and years to come. If the rule is too restrictive in its requirements for states to demonstrate effects, it could discourage the use of cost-effective approaches, inhibit innovation and result in a rule that fails to capitalize on the immense opportunity to reduce greenhouse gas emissions through behaviour change[2]. The response of the EPA and the states on issues such as the scope of acceptable behavioural programmes, and the level and type of documentation required, may determine whether demand-reduction approaches achieve their full potential or whether concern about phantom demand reductions induces the EPA and the states to throw the baby out with the bath water. ❐

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COMMENTARY:

Key threshold for electricity emissions

Christopher Kennedy

To reduce greenhouse-gas emissions in the short term, and catalyse longer-term cuts, countries should reduce the carbon intensity of electricity generation to below a universal target of 600 $tCO_2e\,GWh^{-1}$ by 2020.

When faced with critical global challenges affecting the wellbeing of human society, the nations of the world come together to pursue concrete, measurable, evidence-based goals. Examples include the Millennium Development Goals[1], economic measures for growth or stimulus, and targets for environmental protection. Many numerically expressed global goals have been achieved or partially achieved, while others unfortunately have failed[2]. Key requirements for successfully achieving global goals, expressed in United Nations documents, include the use of robust, relevant measures that are broadly consistent with other global agreements and based on international standards, with well-established data sources[3]. Furthermore, numerical targets should be: ambitious but achievable; quantifiable and time bound; and set in consultation with country teams[4]. Others have pointed to the importance of additional needs:

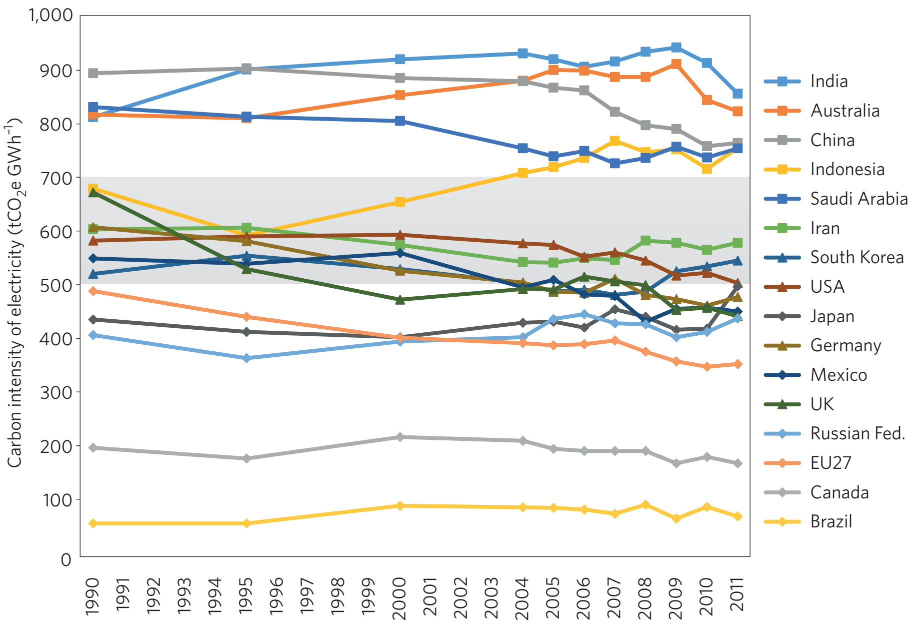

Figure 1 | Carbon intensity of electricity generation. The grey shading indicates the transition zone around the 600-ton threshold in CO_2 emissions, below which electricity generation is carbon competitive. EU27, the 27 member states of the European Union. Data from ref. 10.

articulating visions in terms of inspiring goals; breaking down goals into time-bound, doable propositions; using targets that are universally applicable to all countries, and that can be disaggregated into component measures[2,5,6].

With respect to global climate change, there is political agreement around a single, numerically expressed goal — the 2 °C climate change ceiling (expressed in reports[7] of the UN Framework Convention on Climate Change, UNFCCC). However, supporting universal targets on components of greenhouse-gas (GHG) emissions are absent. The political challenge of reducing global GHG emissions to avoid potentially disastrous impacts of climate change will come to a head in Paris in 2015 at the UNFCCC twenty-first Conference of the Parties, the aim of which will be to achieve a comprehensive agreement on climate change mitigation. The sources of emissions are, of course, many and varied. They include emissions from the energy sector, industrial processes, waste, agriculture, land-use change, and forestry. The nature and magnitudes of sources vary between rich and poor countries, as well as between cities and rural areas, cold and hot locations, mountainous regions and plains. When unpacking the many factors underlying GHG emissions, the carbon intensity of electricity is one of the most important. Here I argue that, above and beyond whatever the parties plan to negotiate, an effort by all nations to reduce carbon emissions from electricity production below ~600 tonnes of CO_2 equivalent (CO_2e) per gigawatt hour by 2020 is essential.

Electrification

Electricity production is itself a substantial direct source of global GHG emissions. In 2012, it accounted for about 30% of the total emissions for Annex 1 (developed) countries. Global electricity production has roughly doubled from 11,873 TWh in 1990 to 22,752 TWh in 2012[8] — and can only be expected to increase further in the next few decades. There is compelling evidence that electricity use is a leading indicator of economic development[9], so it is unrealistic to expect global electricity use to decrease. Indeed, even with much needed conservation measures, it will increase. Nations should be encouraged to step up and aggressively reduce the carbon intensity of their electricity supply — replacing emissions-intensive sources such as coal and oil with renewable sources. This is necessary for cutting emissions from the power sector, but more to the point, it is strategically important for lowering emissions in other sectors too, through electrification.

Electrification is a generic approach that is reflected in several technological strategies for reducing emissions[10]. Examples are the replacement of internal combustion engines with electric or plug-in hybrid electric vehicles, or the replacement of natural gas home furnaces with ground- or air-source heat pumps (which require some electricity to run the pumps). The introduction of high-speed electric trains in place of short-haul flights, or electric trams in place of buses are further examples. Conceivably, over the next few decades many of our fossil-fuel-powered engines and furnaces could be replaced with electric power. Using cleaner energy sources has other benefits, not least of which is less air pollution leading to improved human health. There are also challenges: environmental impacts of battery disposal; resilience of electricity grids; and costs, amongst others. But there is a much greater issue — GHG emissions are only reduced under electrification strategies if the displaced fossil fuels are replaced by electricity of suitably low carbon intensity.

Based on life-cycle environmental studies by industrial ecologists, my colleagues Nadine Ibrahim and Daniel Hoornweg and I previously considered the threshold below which electrification becomes carbon competitive; that is, when markets for electric vehicles and other electrified assets can grow without increasing life-cycle emissions[11]. We estimated the threshold to be about 600tCO_2e GWh^{-1} (hereafter the '600-ton threshold'). This value is based on studies of replacing diesel and gasoline automobiles in Europe and North America, respectively, with equivalent electric vehicles, and the potential use of ground-source heat pumps in Canadian cities. The threshold is not precise — it is more appropriate to consider there to be a transition zone between about 500 and 700 tCO_2e GWh^{-1}. It depends on technical factors such as the efficiencies of engines or pumps, and the performance characteristics of the comparative displaced technology. A further study[10] by the International Energy Agency (IEA) puts the thresholds for electric cars, vans, heavy trucks, passenger trains and freight trains all between 500 and 700 tCO_2e GWh^{-1}.

To many, the goal of countries achieving electricity production under the 600-ton threshold may seem quite unambitious. After all, it is only the threshold at which electric vehicles and gasoline or diesel cars have equivalent (life-cycle) emissions. To actually reduce emissions, the carbon intensity has to be lower — and the lower the better. This is certainly what needs to happen over time. To meet the 2 °C target, the IEA estimates that CO_2 emissions per unit of electricity have to decrease by 90%

by 2050[10]. The 600-ton threshold is just a short-term goal (for 2020) that allows markets for electric products to grow and flourish without doing more harm.

Progress

The good news is that the global average carbon intensity of electricity is already below the 600-ton threshold — but there are regional disparities, and these matter. The IEA[12] reports that the world average carbon intensity for 2011 was 536 tCO_2e GWh^{-1}, which is relatively unchanged since 1990 (524 tCO_2e GWh^{-1}). Differences between countries, however, are quite dramatic. A small number of European countries (Albania, Iceland, Norway and Sweden) and African countries (Congo, Ethiopia, Mozambique and Zambia) as well as Nepal and Tajikistan, have carbon intensities less than 20 tCO_2e GWh^{-1}. This may be due to high use of hydropower — or in the case of Iceland (0 tCO_2e GWh^{-1}) hydro and geothermal. At the opposite extreme are Botswana (1,787 tCO_2e GWh^{-1}), Kosovo (1,109), Estonia (1,086), Turkmenistan (983), Bosnia and Herzegovina (974) and Cuba (955). Fortunately, these are mostly relatively small countries — although they could still do with some help.

Focus on the highest-emitting countries is more important. Figure 1 shows the carbon intensity of electricity production for the 15 overall highest GHG-emitting countries (based on fossil-fuel consumption and cement production only[13]). Ten of the fifteen were already below the 600-ton threshold as of 2011, although eight of these (Russia, the UK, Mexico, Germany, Japan, the USA, South Korea and Iran) are not far below the threshold — ranging from 437 to 538 tCO_2e GWh^{-1}. Brazil (68) and Canada (167) have substantial hydropower generation. The five nations above the proposed threshold include China (764) and India (856) — the first and third highest total emitters — where the world's climate change challenge will be won or lost. Accompanying China and India are Australia, Indonesia and Saudi Arabia, which are all between ~100 and 250 tCO_2e GWh^{-1} above the key 600-ton threshold.

Meeting the threshold

Although not necessarily easy, there are reasonable prospects that the larger nations with high-carbon electricity generation could bring their carbon intensities under the 600-ton threshold by 2020. India is expected to reduce the share of coal in its power mix — and even where it continues to use coal, it could use more efficient state-of-the-art power plants with emissions around 750 tCO_2e GWh^{-1}, compared with its existing coal plants, which average 1,100 tCO_2e GWh^{-1} (ref. 10). India intends to increase its nuclear generating capacity, and also has potential for increased generation from hydropower and other renewable sources. Analysis by the power systems laboratory at Tsinghua University shows that under a base case scenario, power sector emissions in China could be down to 430 tCO_2e GWh^{-1} by 2030, with more progressive scenarios reaching as low as 140 tCO_2e GWh^{-1} (ref. 14). The key technologies for China's low-carbon pathway are high-efficiency coal, and increased hydropower, wind and nuclear generation, all of which are cost competitive. Saudi Arabia has begun expansion of sustainable energy technologies through the King Abdullah City for Atomic and Renewable Energy; while Australia has already learnt how emissions can be reduced through an experiment with carbon pricing (now discontinued). These four nations could lead others with high-carbon electricity generation to decrease below the 600-ton threshold.

Greater reductions in GHG emissions could further be achieved if the 600-ton maximum was pursued at a sub-national level. In federated nations such as Canada, India and the United States, power-sector emissions are in practice under the jurisdiction of state or provincial governments. For example, the US Environmental Protection Agency's proposed new rules on carbon emission from the power sector place much of the emphasis for action on to the individual states[15]. The carbon intensity of electricity can vary considerably between sub-regions of a country. In India, West Bengal is essentially 100% coal powered; electricity in the capital region is predominantly generated from natural gas; and other regions are dominated by hydropower. In Canada, four provinces have grids under 20 tCO_2e GWh^{-1}, while Alberta and Saskatchewan have high carbon intensities (>750 tCO_2e GWh^{-1}). If sub-regions with such carbon-intensive power grids can be encouraged to meet the 600-ton threshold, then this would bring national average intensities down even further.

Longer-term reductions

The short-term goal of reducing the carbon intensity of electricity is also important for catalysing massive cuts in global GHG emissions that may take longer to achieve. As Jacobson and Deluchhi[16] have shown, it may be possible to provide all of the world's electricity needs from renewable sources. Investment in low-carbon power production is also one of three core interactions in global infrastructure that lies at the heart of a potential virtuous cycle of low-carbon growth[17]: increased production of low-GHG electricity enables greening of buildings and transportation vehicles; the resulting lower demand for oil and natural gas reduces the need for new infrastructure in these sectors; and the capital is alternatively invested in decarbonizing the electricity sector, hence decreasing demands for coal. This cycle may be economically viable because of cost savings that occur with railways and port infrastructure, where freed-up capacity (45% previously used to convey fossil fuels) is used to support global trade in components of green infrastructure. Although this is a tentative description of a low-carbon infrastructure system with many technical and social issues to be resolved, getting electricity production under the 600-ton threshold by 2020 would be a significant first step. ❐

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