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Geoengineering cities to stabilise climate

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Geoengineering typically refers to planetary-scale or perhaps regional-scale technological responses to the deleterious effects of human-induced climate change. This paper explores the idea that urbanisation could constitute a successful form of distributed, bottom-up geoengineering. Through the redesign of existing urban areas and the creation of more efficient new ones, per capita energy consumption and carbon dioxide generation could potentially be radically reduced. However, implementing these changes requires a combination of new technology and altered behaviour, coordination across sectors and geography, and unusually strong political action. In particular, civil engineers and economists would need to create methods for determining the most cost-effective ways for each city to become more resource efficient. Urban redesign carries a lower risk and offers more ancillary benefits than most other geoengineering schemes. Given the potentially catastrophic consequences of global warming, engineers, planners and politicians need to calculate how quickly and extensively cities can change to become positive forces for repairing the climate.

1. Urbanisation as a model for geoengineering

Geoengineering refers to a set of practices and technologies that aim to manipulate the Earth's environment to counteract the negative effects of anthropogenic greenhouse gas (GHG) emissions (Keith, 2000). For instance, giant reflectors might be constructed in space to reduce the amount of sunlight hitting the Earth's surface. Coupled with mitigation and adaptation strategies, geoengineering can in theory contribute to the amelioration of other profound challenges facing society, including resource depletion, poverty and biodiversity loss. But most such proposals involve largely unproven technologies and raise serious concerns about excessive costs and unintended consequences (McKibben, 2010). They also tend to be monolithic in design and massive in scale, and downplay the potential benefits derived from modifying human behaviour. Furthermore, they minimise the extreme governance challenges associated with policies and decisions that can potentially affect all countries, regions and species on Earth (Broykin *et al.*, 2009).

The redesign of cities is not commonly classified as geoengineering, although in many ways urbanisation can be seen as the largest ongoing experiment in planetary-scale manipulation (Bugliarello, 2001). Cities are where more than half the world's population lives, most resources are consumed and most pollution is generated. They thus have a physical and biological influence that extends far beyond their borders (Girardet, 1999). Through economies of scale and system integration, cities hold the potential of greatly reducing per capita consumption and waste production, helping to accomplish the climate-stabilising goals of geoengineering (Brand, 2009).

To date, the closest this promise has come to realisation is in relatively wealthy and socially conscious cities like Copenhagen in Scandinavia and Vancouver in the Cascadia corridor of North America, where social attitudes, public policy and administrative practice are working in concert with temperate climates and enabling infrastructure to reduce environmental impact. But, with a few exceptions, these efforts have been limited to isolated buildings, neighbourhoods and districts. Futuristic urban experiments such as Masdar, now under construction in the United Arab Emirates, and the now-abandoned Dongtan project near Shanghai are attempting to make carbon dioxide emission reduction effortless for individual citizens but the economic viability and scalability of these mini-utopias is far from proven and full life-cycle assessments of their true carbon costs are ambiguous (Sahely *et al.*, 2005).

Carbon or ecological footprint calculations show that the centres of the densest cities, like New York and Hong Kong, yield some of the least pollution per capita because car ownership is difficult while mass transit is affordable and extensive (Owen, 2010). In wealthier countries this benefit is somewhat offset by high consumption in the surrounding suburbs (Newman, 2006). Many of today's fastest growing cities, which are found in developing nations, still have relatively small carbon dioxide emissions because of low average incomes (Hardoy *et al.*, 2001). However, they aspire to acquire the material benefits of western society for their rapidly expanding populations, which would eventually result in large increases in the generation of carbon dioxide emissions. This reality adds urgency to the need to more purposefully view cities as central to climate solutions.

The main argument of this paper is that, if properly conceived, executed and coordinated across the world, urban redesign could be among the most effective and realistic ways to relieve the global atmospheric crisis (e.g. Calthorpe, 2010). In contrast to more extreme technological proposals like injecting sunlight-reflecting aerosols into the stratosphere (Crutzen, 2006) or deploying vast arrays of carbon-dioxide-removing scrubbers (Lackner, 2002), making cities more efficient would have many ancillary dual-use benefits beyond climate, like providing jobs, increasing resilience to natural and man-made disasters and improving the health and quality of life of residents (Allenby and Fink, 2005). It has not yet been shown that a combination of architecture, engineering, public policy, administrative practice, market mechanisms and social media can be used intentionally to achieve climate goals. The focus here is on the need for a quantitative evaluation of alternatives coupled with unprecedented coordination across scales, tools, sectors and regions, in order for urban design to become an effective means of climate repair, precluding heroic geoengineering efforts.

2. Managing climate stabilisation

One of the largest barriers to attempting to slow or reverse climate change has been the widespread perception that it cannot be accomplished under current technological, demographic, and economic conditions (e.g. McKibben, 2012). Against this backdrop, a few different carbon dioxide emission reduction methods have offered plausible paths to climate stabilisation without the geoengineering risk of ecological catastrophe.

Pacala and Socolow (2004) calculated how global carbon dioxide emissions could first be held at then current levels (7 billion tonnes (Gt) of carbon per year) for 50 years, followed by a half century in which new innovations, some of which have not yet been invented, would allow global carbon dioxide emissions to drop to near zero. Their model attempted to take into account increases in population and standard of living. The initial stabilisation phase would require a combination of technological and policy steps, grouped into 15 categories, all of which would need to be put in place together to reach 7 Gt of carbon dioxide emissions avoided, as follows

- make vehicles more fuel efficient
- reduce vehicle use
- make buildings more energy efficient
- make coal-fired power plants more efficient
- shift coal-based plants to natural gas
- sequester carbon dioxide captured at coal-fired plants
- sequester carbon dioxide from hydrogen plants
- sequester carbon dioxide from coal-to-synfuels plants
- substitute nuclear fission for coal power
- replace coal with wind power
- replace coal with photovoltaics
- use wind power to separate hydrogen for use in hybrid cars
- replace fossil fuels with biomass fuels
- expand the area of carbon-dioxide-absorbing tropical forests
- expand the use of conservation tillage in agriculture.

In their widely cited graph (Figure 1), the carbon dioxide emissions that need to be avoided to stabilise the climate in 50 years were represented as a triangle made up of seven wedges, each of which represented 1 Gt of carbon. In an update, Socolow (2011) noted that nine wedges would then be needed because of the acceleration of carbon dioxide emission rates.

McKinsey and Co. and their collaborators have developed an alternative way of illustrating global carbon dioxide abatement (Enkvist *et al.*, 2007). They produced curves representing the carbon dioxide emission reduction costs and benefits of over 60 different technologies and policies that either are available today or are likely to be available in the near future. They plot these options as vertical bars whose widths correspond to the amount of carbon dioxide emission saved and whose heights are proportional to cost (Figure 2). Roughly one-third of the opportunities, such as making lighting systems more efficient or retrofitting residential heating, ventilation, and air-conditioning systems would provide immediate net savings,

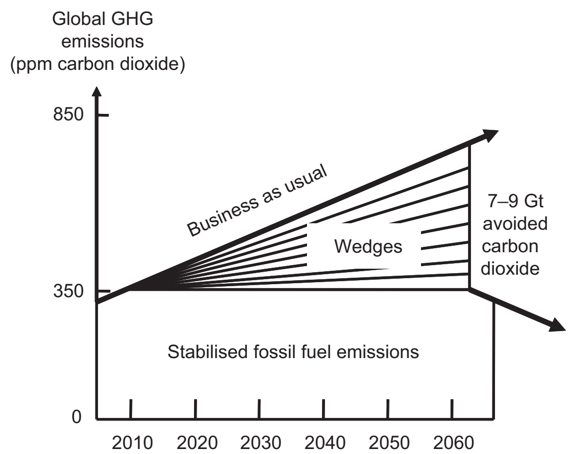

Figure 1. Schematic diagram, after Pacala and Socolow (2004), illustrating how 'wedges' of avoided carbon dioxide emissions can help keep down atmospheric carbon dioxide

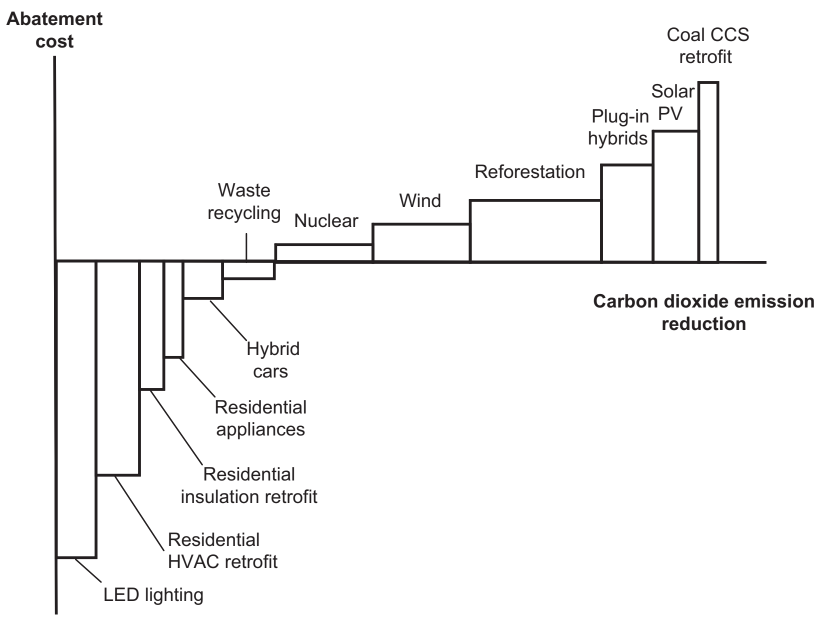

Figure 2. Simplified, schematic McKinsey diagram showing carbon dioxide abatement costs and benefits (after Enqvist *et al.*, 2007); CCS, carbon dioxide capture and geological storage; HVAC, heating, ventilation and air conditioning; LED, light-emitting diode; PV, photovoltaic

and thus appear as downward-pointing rectangles, indicating negative costs. Others, like shifting from coal to natural gas or expanding wind and solar generation, have positive costs matched to significant carbon dioxide savings. The McKinsey approach helps calculate the price tag of achieving any particular level of reduction in carbon dioxide emissions.

When they were originally presented in 2004 and 2006, respectively, these two approaches showed how combinations of existing methods could, in theory, significantly reduce global carbon emissions. But translating such concepts into practice requires a considerably more detailed analysis, which has subsequently been undertaken by a cottage industry of researchers exploring the promise and limits of these and other models. This follow-on work has, for example, calculated the contributions required by each wedge or rectangle of carbon dioxide emissions avoided, along with a list of problematic issues that might affect implementation. Pacala and Socolow's original 15 categories were considered to be illustrative. Alternatives could be substituted, based on changes in technology, politics, economics and the climate. For instance, the 2008 recession temporarily reduced global emissions, partly ameliorating the lack of progress made in international climate negotiations in the preceding decade. Recently increased passenger vehicle corporate average fuel economy standards in the USA (Vlasic, 2012) may help achieve the target for auto efficiency (policy step no. 1). Similarly, the discovery of extensive, relatively cheap shale gas deposits in the USA offers the possibility of a more rapid substitution of natural gas for coal (policy step no. 5), although the environmental costs of gas extraction are likely to be high. On the other hand, the Fukushima nuclear disaster has slowed progress towards the increased use of fission power plants (policy step no. 9). Meanwhile, numerous McKinsey studies have calculated cost-abatement curves for individual countries such as Australia (Lewis and Gomer, 2008) and cities like London (Denig, 2009).

The largest obstacles to implementing stabilisation strategies like those described above are not technological but political. No global organisation has the authority to oversee, coordinate or enforce the required policy shifts (Fink, 2011). Internationally, governments' acceptance of the need to address climate change varies widely, with the largest polluters like the USA and Australia taking the least responsibility. Even at the national scale, different regions of a country can have very different views and priorities, based on their climate, industrial base, energy resources and politics, preventing the formation of the type of consensus needed for leaders to be willing to act.

This is where cities may play a uniquely helpful role. For the past 20 years mayors and municipal governments have become increasingly proactive and progressive about climate policy (Bai, 2007; Kousky and Schneider, 2003; Rosenzweig *et al.*, 2010). Aggressive climate action plans are being developed, shared and incorporated into strategic visions for cities around the world, although to date only a few have spent significant financial and political capital to achieve these ends. Organisations like C40 Cities (Climate Leadership Group), ICLEI, the World Bank, UN Habitat and the Urban Sustainability Directors' Network, and companies like IBM, Siemens and Cisco Systems have been facilitating information exchange among cities. Shifting climate policy leadership away from countries to their largest cities would seem to increase the chances that carbon dioxide emission reduction strategies like these could be implemented.

3. City climate action plans as tools for climate stabilisation

Just as with the Pacala and Socolow wedge approach and McKinsey's carbon dioxide emission abatement curves, cities' climate action plans typically divide the generation of carbon dioxide emission reduction into numerous categories, corresponding to municipal functions and offices. For example, one of the first such plans in the USA, developed by the City of Portland, Oregon and surrounding Multnomah County in 1992 and updated in 2009 targets (a) more energy-efficient buildings, (b) denser urban form, (c) reduced generation of solid waste, (d) expanded urban forestry, (e) less resource-intensive food production, (f) greater community involvement, (g) more intentional adaptation strategies and (h) fewer carbon dioxide emission-intensive government operations (City of Portland and Multnomah County, 2009). Under these eight broad headings are 18 objectives to be reached by 2030 (e.g. achieve zero net GHG emissions in all new buildings and homes) and 92 actions to be substantially addressed by 2012 (e.g. establish a city business tax credit for installing solar panels and ecoroofs together). This smorgasbord approach is typical of cities, which adopt a range of strategies to collectively achieve a number of different policy objectives.

In order for integrated city-scale carbon dioxide emission reduction to be effective at the national and global scale, different urban areas need to measure similar factors in similar ways. A look at a second climate action plan shows how challenging it is to achieve this compatibility. *PlaNYC*, adopted by New York City in 2007 (Bloomberg and New York, 2007), includes six climate-related goals: (a) reduce and track GHG emissions, (b) assess vulnerabilities and risks from climate change, (c) increase the resilience of the city's built and natural environments, (d) protect public health from the effects of climate change, (e) increase the city's preparedness for extreme climate events and (f) create resilient communities though public information and outreach. As in Portland, each of these goals includes several action items, like release an annual inventory of GHG emissions or partner with the Federal Emergency Management Agency to update flood insurance rate maps.

While Portland and New York City have comparable overall goals, their climate action plans differ in detail and emphasis. This complicates attempts to quantify the implications of such plans for reducing carbon dioxide emissions, both individually and collectively. In both cases, only some of the climate objectives can be translated directly into carbon dioxide emissions (e.g. reduce the total energy use of all Portland's buildings built before 2010 by 25%). Others (e.g. create more intentional adaptation strategies) cannot, at least not without considerable subjective interpretation. Nonetheless, with a concerted effort by city officials, environmental engineers, urban geographers and computer scientists it should be possible to sum most of the climate mitigation strategies being undertaken by the world's cities and calculate how much total carbon dioxide emission reduction they could accomplish according to different models. This information could be presented using municipal equivalents of Pacala and Socolow's set of wedges of avoided carbon dioxide emission or the McKinsey cost curves, or some other agreed-upon standards. These diagrams and associated data compilations could be used to total the potential carbon dioxide emission reduction that could be achieved by individual cities and by all cities acting in concert.

In order for municipal actions to collectively be considered viable alternatives to geoengineering, the aggregate of their potential carbon dioxide emission reductions needs to be great enough to attain climate stabilisation – 9–11 Gt by 2061, according to Socolow's 2011 revision of his 2004 paper with Pacala. Of their 15 original carbon dioxide emission reduction strategies, only two take place entirely within city limits: reducing vehicle use and making buildings more energy efficient. However, the consumption footprints of cities extend far into the surrounding countryside and, through their supply chains and waste streams, throughout the world. Mobilising city dwellers is generally easier than getting their counterparts in rural areas or states and countries as a whole to take action. This is particularly true in metropolitan centres with progressive social norms like Seattle, San Francisco and Portland in the USA. The most far-sighted climate action plans thus take into account not only those activities that occur completely within a city's borders but also those that are indirectly influenced by its population. Deciding how many levels to take this analysis is a challenge that continues to face environmental engineers (Ramaswami *et al.*, 2008).

For example, the fuel mix in the power plants that supply a city can be changed in response to public pressure, even if those facilities are far from the urban core. Portland receives much of its electricity from a coal-fired power plant 250 km east of the city in the town of Boardman. When they realised that they were largely dependent on such a dirty fuel source, the people of Portland worked with the Oregon Department of Environmental Quality to persuade the local utility, Portland General Electric, to close the facility 20 years before its scheduled decommissioning (Learn, 2010). While economic factors like the cost of required abatement technology played a major role in the decision, public attitudes in Portland were also important. Other seemingly non-urban opportunities to reduce emissions, ranging from changing agricultural policies affecting urban food supplies, to restricting trans-shipments of carbon-dioxide-intensive fuels like coal through urban ports, or encouraging shifts to hybrid and all-electric vehicles, can similarly be influenced by the actions of people in cities.

While it cannot yet be demonstrated conclusively that cities hold the potential to mitigate all the deleterious climate effects of carbon dioxide emissions as quickly as some geoengineering schemes propose, places like Portland offer positive signs of such mitigation. Through a combination of diverse public policy steps and citizen engagement, including the climate action plan cited earlier, in 2010 Portland became the first major US city to successfully lower its carbon dioxide emissions, both per capita and total, below 1990 levels, despite a more than 20% population growth. Initial progress could be explained by the extensive mass transit system and compact downtown that resulted from Oregon's urban growth boundary policy enacted in the 1970s. A more recent focus on recycling and municipal-scale composting, coupled with the expansion of renewable energy as a share of the city's power supply, have continued to bring down emissions. But today's carbon dioxide output is still far above where it needs to be in order to achieve climate stabilisation by the mid-twenty-first century. The next steps to carbon dioxide emission reduction will be more technically challenging and expensive, requiring continuing political support in the face of conflicting pressures to promote job growth and social equity. Given that much of Portland's recent economic development is linked, at least in terms of perceptions, to its reputation for environmental stewardship, public receptivity to climate-sensitive policies is likely be higher there than in other parts of the USA. Furthermore, as has been shown elsewhere, there are still many untapped policies that are effective in terms of cost, energy and carbon dioxide emissions in both the short term and long term.

Another example of how cities can calculate the feasibility of lowering their carbon dioxide output is derived from the Stern review on the economics of climate change (Stern, 2006), originally commissioned by the British government in 2005. This report laid out a series of economic arguments in favour of global carbon reduction. More recently, a mini-Stern review (Gouldson *et al.*, 2013) was prepared for the English city of Leeds to evaluate the cost-effectiveness of hundreds of low-carbon-dioxide-emission options that could be applied to its metropolitan area. In contrast to the McKinsey carbon dioxide emission abatement curves and the Pacala–Socolow wedges, the mini-Stern assessment looks primarily at the economic characteristics of different actions: capital costs, operational costs, hidden costs, energy savings, financial savings and savings in carbon dioxide emission. The report concludes that by 2022 Leeds could reduce its emissions relative to 1990 levels by as much as 40% through a combination of local infrastructure investments, conservation and the adoption of less carbon-intensive energy production at the national level.

If climate-related urban policy changes had only positive effects, their implementation would be uncontroversial. In reality, there are nearly always complex trade-offs associated with sustainability solutions. For instance, expanding city parks can result in more trees absorbing carbon dioxide but can also reduce population density, thus increasing vehicle miles travelled through the city. Vigulé and Hallegatte (2012) used an integrated city model to show that the impacts of three possible development options for Paris – a greenbelt policy, zoning to reduce flood risk and subsidising public transport – combine in a highly non-linear way, leading to more politically viable and cost-effective strategies for carbon dioxide emission reduction than if the policies were enacted in isolation. Quantitative tools like these can help policymakers choose optimum climate mitigation options.

A coordinated strategy that combines city-oriented versions of policies and technologies like those incorporated in the Pacala–Socolow wedges, the McKinsey carbon dioxide emission abatement cost curves and the mini-Stern economic analyses could form the basis for a more general, urban-based carbon dioxide emission reduction scheme. It would require complex agreements about standards for the data gathering and presentation of carbon dioxide emission facts, similar to plans promoted by ICLEI and the global city indicators facility for obtaining consistent urban indicators (McCarney, 2012). Such protocols could in turn quantify the way that ultra-efficient cities could achieve climate mitigation goals for themselves, for their countries and for the world. Funding agencies, private foundations, university researchers and companies could make a concerted effort to demonstrate the cost–benefit ratios of carbon dioxide emission reduction by urban actions compared with geoengineering.

Despite the political backlash against climate science in the USA in recent years, the steady progression of natural disasters like 2012's Hurricane Sandy, Midwest drought and Western forest fires will inevitably move popular opinion towards accepting the importance of directly addressing human-caused climate change. Once that shift occurs, policymakers will seek to implement readily available solutions, preferably ones that retain as many business-as-usual consumption patterns as possible. Proponents of radical geoengineering strategies are then likely to jump at the opportunity to advance their favourite projects. In order to offer a compelling, practical and less destructive alternative, cities will need to show that the steps described in this paper, taken together, could just as effectively address the build up of atmospheric carbon dioxide. Planning for that political debate would be most effective if it began now, prior to when possible disaster strikes. A critical unresolved question is who can act as the coordinating body to organise a global urban response that takes responsibility for moving society towards carbon dioxide emission neutrality, so that infrastructure and peoples' lives are made more efficient and resilient, en route to reversing the negative atmospheric changes that technology has caused over the past century.

4. Conclusion

This paper suggests that cities be viewed as engines for intentional climate change mitigation, combining the efficiencies of urban density (including reduced vehicle miles travelled, lower per capita heating and cooling costs) with the more effective governance found in many municipal jurisdictions today. City climate action plans are critical roadmaps to net zero carbon dioxide emissions. In the context of earth systems engineering, climate-friendly urban policies represent collective bottom-up actions that can have a global impact. These are in stark contrast to the top-down philosophy inherent to geoengineering.

In order to be taken seriously by the technocratic fans of geoengineering, the combined benefits of urban policies towards reducing carbon dioxide emissions will need to be rigorously quantified and shown to be both significant and attainable. For example, a recent analysis by Heidrich *et al.* (2013) has shown that 30 cities in the UK (comprising 27% of the UK's population) plan, on average, to reduce carbon dioxide emissions by 32%. Because the largest cities are the most ambitious, this actually equates to a 54% per capita reduction. New government, academic and industrial research programmes will need to carry out these types of analyses and common ways of defining goals for different cities will be needed. Splitting daunting overall targets into more feasible parts, using methods like those of McKinsey, Socolow or Stern, can help avoid discouragement.

Distinctions will also need to be made between the pathways available to cities in developed and developing nations. Urban options in economically advanced countries largely consist of incremental improvements in the energy efficiency of the built environment and individual behaviour choices, leading to reduced carbon dioxide emissions from transportation and consumption. In contrast, less developed countries, where urbanisation is most rapid, have huge opportunities to avoid locking in decades of excessive energy consumption through the improved design of transportation networks, land use plans, construction standards and industrial supply chains (Hardoy *et al.*, 2001). Aligning city planners and urban policymakers in developed and developing countries behind a common vision of climate mitigation is also essential (Socolow, 2012).

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