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Geoengineering cities to stabilise climate

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4547 (text, figure captions, references)

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Abstract

Geoengineering typically refers to planetary, 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 redesign of existing urban areas and creation of more efficient new ones, per capita energy consumption and CO\textsubscript{2} 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 would carry lower risk and offer more ancillary benefits than most other geoengineering schemes. Given global warming’s potentially catastrophic consequences, engineers, planners and politicians need to calculate how quickly and extensively cities could shift to become positive forces for climate repair.

Keywords: Public Policy, Town and City Planning, Energy Conservation
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 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, massive in scale, and downplay the potential benefits derived from modifying human behaviour. Furthermore, they minimize 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, where more than half the world’s population lives, the majority of resources are consumed, and the most pollution is generated, have 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-stabilizing goals of geoengineering (Brand, 2009).

To date, the closest this promise is coming to realization 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 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, in developing nations, still have relatively small carbon emissions because of low average incomes (Hardoy et al, 2001). However, their aspirations are to acquire the material benefits of western society for their rapidly expanding populations, which would eventually result in large increases in CO₂ generation. 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 CO$_2$-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). Using a combination of architecture, engineering, public policy, administrative practice, market mechanisms and social media as an intentional way to achieve climate goals is an as-yet unproven exercise. The focus here is on the need for 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 technologic, demographic, and economic conditions (e.g., McKibben, 2012). Against this backdrop, a few different carbon reduction methods have offered plausible paths to climate stabilisation without geoengineering’s risk of ecological catastrophe.

In 2004, Pacala and Socolow calculated how global carbon emissions could first be held at then-current levels (7 billion tons [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 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 technologic and policy steps, grouped into 15 categories, the sum of which would need to reach 7 Gt of avoided carbon emissions: (1) make vehicles more fuel efficient, (2) reduce vehicle use, (3) make buildings more energy efficient, (4) make coal-fired power plants more efficient, (5) shift coal-based plants to natural gas, (6) sequester CO$_2$ captured at coal-fired plants, (7) sequester CO$_2$ from H$_2$ plants, (8) sequester CO$_2$ from coal-to-synfuels plants, (9) substitute nuclear fission for coal power, (10) replace coal with wind power, (11) replace coal with photovoltaics, (12) use wind power to separate H$_2$ for use in hybrid cars, (13) replace fossil fuels with biomass fuels, (14) expand the area of CO$_2$-absorbing tropical forests, and (15) expand the use of conservation tillage in agriculture. In their widely cited graph (Figure 1), the avoided carbon necessary to stabilise climate in 50 years was represented as a triangle made up of 7 “wedges,” each of which represented 1 Gt of carbon. In a 2011 update, Socolow noted that 9 wedges would then be needed, because of the acceleration of emission rates.
Figure 1. Schematic diagram, after Socolow and Pacala (2004), illustrating how “wedges” of avoided carbon emissions can help keep down atmospheric CO₂. See text for details.

McKinsey and Company and their collaborators have developed an alternative way for illustrating global carbon abatement (Enkvist et al., 2007). They produced curves representing the carbon reduction costs and benefits of over 60 different technologies and policies that either are available today or likely will be in the near future. They plot these options as vertical bars whose widths correspond to the amount of carbon saved and whose heights are proportional to cost (Figure 2). Roughly a third of the opportunities, such as making lighting systems more efficient or retrofitting residential HVAC (heating, ventilation, and air conditioning) systems would provide immediate net savings 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 savings. The McKinsey approach helps calculate the price tag of achieving any particular level of carbon reduction.

![McKinsey Diagram](image)

Fig. 2. Simplified, schematic McKinsey diagram showing CO₂ abatement costs and benefits (after Enqvist et al., 2007).

When 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 considerably more detailed analysis, which has subsequently been undertaken by a cottage industry of research designed to explore 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 avoided carbon, along with a list of problematic issues that might affect implementation. Pacala and Socolow’s original 15 categories were considered illustrative—alternatives could be substituted, based on changes in technology, politics, economics, and 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 CAFE (Corporate Average Fuel Economy) standards in the U.S. (Vlasic, 2012) may help achieve the target for auto efficiency (policy step #1). Similarly, the discovery of extensive, relatively cheap shale gas deposits in the U.S. offers the possibility of more rapid substitution of natural gas for coal (policy step #5), although non-climate environmental costs of gas extraction will likely be high. On the other hand, the Fukushima nuclear disaster has slowed progress toward increased use of fission power plants (policy step #9). Meanwhile, numerous McKinsey studies have calculated cost-abatement curves for individual countries (e.g., Australia: Lewis and Gomer, 2008) and cities (e.g., London: Denig, 2009).

The largest obstacles to implementing stabilisation strategies like those described above are not technological but political: no global organization has the authority to oversee, coordinate, or enforce the required policy shifts (Fink, 2011). Internationally, governmental acceptance of the need to address climate change varies widely, with the largest polluters like the U.S. 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 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 (Kousky and Schneider, 2003; Bai, 2007; 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. Organizations like C40 Cities (Climate Leadership Group), ICLEI (Local Governments for Sustainability), the World Bank, UN Habitat, 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 reduction strategies like these could get implemented.

3. City climate action plans as tools for climate stabilisation

Just as with the Pacala and Socolow “wedge” approach, and McKinsey’s carbon abatement curves, cities’ climate action plans typically divide avoided carbon generation into numerous categories, corresponding to municipal functions and offices. For example, one of the first such plans in the U.S., developed by the City of Portland, Oregon and surrounding Multnomah County in 1992 and updated in 2009 targets (1) more energy-efficient buildings, (2) denser urban form, (3) reduced generation of solid waste, (4) expanded urban forestry, (5) less resource intensive food production, (6) greater community involvement, (7) more intentional adaptation strategies, and (8) less carbon-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 greenhouse gas 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 reduction to be effective at the national and global scale, different urban areas would 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 (NY), 2007), includes six climate-related goals: (1) reduce and track GHG emissions, (2) assess vulnerabilities and risks from climate change, (3) increase the resilience of the city’s built and natural environments, (4) protect public health from the effects of climate change, (5) increase the city’s preparedness for extreme climate events, and (6) 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 FEMA [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 carbon reduction implications of such plans, both individually and collectively. In both cases, only some of the climate objectives can be translated directly into carbon emissions (e.g., “reduce the total energy use of all [Portland’s] buildings built before 2010 by 25 percent”); others (e.g., “create more intentional adaptation strategies”) cannot, at least not without considerable subjective interpretation. Nonetheless, with 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 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, or the McKinsey cost curves, or some other agreed-upon standards. These diagrams and associated data compilations could be used to tally up the potential carbon 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 reductions needs to be great enough to attain climate stabilisation—9-11 Gt by 2061 according to Socolow’s 2009 revision of his 2004 paper with Pacala. Of their 15 original carbon 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 U.S. 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 indirectly influenced by its population. Deciding how many levels to take this analysis is a challenge that environmental engineers continue to debate (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 realized 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 can similarly be influenced by the actions of people in cities, ranging from changing agricultural policies affecting urban food supplies, to restricting transshipments of carbon-intensive fuels like coal through urban ports, or encouraging shifts to hybrid and all-electric vehicles.

While we cannot yet demonstrate conclusively that cities hold the potential to mitigate all of the deleterious climate effects of carbon emissions as quickly as some geoengineering schemes propose, places like Portland offer positive signs. Through a combination of diverse public policy steps and citizen engagement, including the Climate Action Plan cited earlier, Portland in 2010 became the first major U.S. city to successfully lower its carbon emissions, both per capita and total, below 1990 levels, despite 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 expansion of renewable energy as a share of the city’s power supply have continued to bring down emissions. But today’s carbon output is still far above where it needs to be in order to achieve climate stabilisation by the mid 21st Century. The next steps to carbon 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 perception, to its reputation for environmental stewardship, public receptivity to climate-sensitive policies will likely be higher than in other parts of the U.S. Furthermore, as has been shown elsewhere, there are still many untapped policies that are cost-, energy- and carbon-effective in both the short and long term.

Another example of how cities can calculate the feasibility of lowering their carbon output is derived from the “Stern Review on the Economics of Climate Change (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 options that could be applied to its metropolitan area. In contrast to the McKinsey carbon abatement curves and the Pacala-Socolow wedges, the “mini-Stern” assessment looks primarily at economic characteristics of different actions: capital costs, operational costs, hidden costs, energy savings, financial savings, and carbon savings. 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 adoption of lower carbon energy production at the national level.

If climate-related urban policy changes had only positive effects, implementation would be without controversy. In reality, there are nearly always complex trade-offs associated with sustainability
“solutions.” For instance, expanding city parks can result in more carbon-absorbing trees, but can also reduce density, increasing vehicle miles travelled. 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 subsidizing public transport—combine in a highly non-linear way, leading to more politically viable and cost-effective strategies for carbon reduction than if the policies were enacted in isolation. Quantitative tools like these can help policy-makers choose optimum climate mitigation options.

A coordinated strategy that combines city-oriented versions of policies and technologies like those incorporated in the Pacala and Socolow wedges, the McKinsey carbon abatement cost curves, and the mini-Stern economic analyses, could form the basis for a more general, urban-based carbon reduction scheme. It would require complex agreements about standards for carbon-related data gathering and presentation, 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 how 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 carbon reduction cost-benefit ratios of urban actions compared to geoengineering.

Despite the political backlash against climate science in the U.S. 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 to an acceptance of the importance of directly addressing human-caused climate change. Once that shift occurs, policy-makers will look to implement readily available solutions, preferably ones that retain as many “business-as-usual” consumption patterns as possible. Proponents of radical geoengineering strategies will then likely jump at the opportunity to advance their favourite projects. In order to offer a compelling, practical, and less destructive alternative, cities would need to show that the steps described in this paper, taken together, could just as effectively address the build-up of atmospheric carbon. 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 organize a global urban response that takes responsibility for moving society toward carbon 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 (reduced vehicle miles travelled, lower per capita heating and cooling costs, etc.) with the more effective governance found in many municipal jurisdictions today. City climate action plans are critical roadmaps to carbon neutrality. 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 carbon reduction benefits of urban policies will need to be rigorously quantified and shown to be both
significant and attainable. For example, recent analysis by Heidrich et al (in press) has shown that 30 UK cities (comprising 27% of the UK’s population) plan, on average, to reduce emission 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 programs will need to carry out these types of analyses, and common ways of defining goals for different cities will need to be defined. Splitting daunting overall targets into more feasible parts, using methods like McKinsey’s, Socolow’s, or Stern’s, 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 emissions from transportation and consumption. In contrast, less developed countries where urbanization 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 policy-makers in developed and developing countries behind a common vision of climate mitigation is also essential (Socolow, 2012).

5. References


6. Figure Captions

1. Schematic diagram, after Socolow and Pacala (2004), illustrating how “wedges” of avoided carbon emissions can help keep down atmospheric CO\textsubscript{2}. See text for details.

2. Simplified, schematic McKinsey diagram showing CO\textsubscript{2} abatement costs and benefits (after Enqvist et al., 2007).
Global GHG Emissions (ppm CO₂)

7-9 Gt avoided carbon

Business As Usual

wedges

Stabilised fossil fuel emissions

Figure 1
Abatement Cost

CO₂ Reduction

Figure 2

- LED lighting
- Residential HVAC Retrofit
- Residential Insulation Retrofit
- Residential Appliances
- Hybrid cars
- Nuclear
- Wind
- Reforestation
- Plug-in hybrids
- Solar PV
- Coal CCS retrofit
- Waste Recycling
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March 3, 2013

Dear Sarah,

Thank you for your letter containing comments from the referees and the editor about my manuscript. I have incorporated all of the suggestions from Reviewer #2 and most of those from #1 and the editor. I am reproducing the latter two sets of comments here and will include my responses immediately following, marked by "*".

Editor's Comments:

Given the nature of the paper as a review, I also think it would be useful to reflect on the context of cities in the ESE framework - collective bottom up action having a global impact.

* I have added a comment about the ESE framework in the first paragraph of the new "Conclusion" section.

Two other papers published in The Bridge (vol 31, no 1) some time ago might be useful to look at: http://www.nae.edu/Publications/Bridge/EarthSystemsEngineering7311.aspx

* I have cited the first of these papers (Buglierello), but did not feel that the second one added much new to the discussion.

A couple of papers will help deal with the tradeoffs issue that have been raised:
but also see Vigué and Hallegatte. 2012. Trade-offs and Synergies in Urban Climate Policies. Nature Climate Change 2 (3)

* I was not able to obtain the first of these articles in our library so I requested a copy from Rich Dawson. However, I believe that the second article adequately frames the tradeoffs issue. I've now added a new paragraph on this topic, at the bottom of page 8.

Given the nature of R#1's comments what I think would be most useful is to provide a clear summary of, on the basis of the review, what are the key steps forward that brings the paper's arguments all together again and point the way for cities as forces for positive geoengineering efforts. Can I also suggest taking a look at Bruce Beck's work:
http://cfgnet.org/

* I have added a new concluding section that attempts to do what the editor suggested. I looked at Beck's work on the website, but did not find anything that added substantially to the manuscript.

Please provide a 'response to reviewers' document when resubmitting the paper, highlighting how these points have been responded to. A paper receiving a B1, minor
changes required, decision - as yours has - is not usually re-reviewed, only assessed by
the Editor. However, it may be sent out for further review if it is not clear to the editorial
team how, and to sufficient depth, the points have been addressed.

Reviewer #1:
This is a very well written paper - easy to read with an excellent structure. I have almost
no comments concerning style, layout etc - these are all very good.

My concern is that this is a review paper, and I am not sure if this is what the journal
wants.

You mention Dongtan, Masdar, The Stern Review, carbon stabilisation wedges which
will be familiar to some. In many ways the manuscript would make an excellent
introduction document to students / researchers new to this topic. The author is
highlighting the potential of the changing built environment in relation to the carbon
wedges analysis - but I feel this is understood already by many people in this field. Given
the spread of city examples cited it may be useful to explore some of the differences
between the developed and developing world challenges (often one of retrofit in the
former, new build opportunities in the latter).

* I have added a sentence at the end of the paper about the differences between the
opportunities in cities in developed and developing countries.

Unfortunately, the goal posts have shifted somewhat since the 2004 Socolow and Pacala
paper - the targets in 2013 to achieve this level of carbon stabilisation are far more
aggressive - the author should update the figures to reflect new targets.

* I updated the text to further reflect Socolow's comments on the need to revise the
original number of wedges and the timeline. I did not change Figure 1 however, since it is
only intended to illustrate the concept of "wedges," not their quantitative detail.

Dongtan didn't happen - for a variety of reasons! - this should be mentioned and
discussed somewhere.

Masdar, does it really make sense to encourage development in a location with no natural
resources apart from oil and gas? Again, this would make for an interesting discussion
point.

* I added mention that the plans for Dongtan were abandoned; I had already stated that
"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." I believe this addresses
the questions raised by the reviewer.

It is worth recognising in some way the complexity of cities and the, often non-intuitive,
tradeoffs associated with well intentioned plans. How can cities cope with these and how
do the approaches explored in the paper help this.
* As mentioned above, I added a paragraph about tradeoffs, citing Vigule and Hallegatte's work.

Please use subscripts where appropriate e.g. CO2, H2

* Done.