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Exploring the economic case for climate action in cities

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ABSTRACT

There is increasing interest in the potential of cities to contribute to climate mitigation. Multiple assessments have evaluated the scale and composition of urban GHG emissions, while others have evaluated some aspects of urban mitigation potential. However, assessments of mitigation potential tend to be broadly focused, few if any have evaluated urban mitigation potential on a measure-by-measure basis, and fewer still have considered the economic case for investing in these measures. This is a significant knowledge gap as an economic case for action could be critical in building political commitment, strengthening institutional capacities, securing large-scale finance and targeting investment and implementation in cities. In this paper, we conduct a comparative analysis of the results of five recently completed studies that examined the economic case for investing in low-carbon measures in five cities: Leeds in the UK, Kolkata in India, Lima in Peru, Johor Bahru in Malaysia and Palembang in Indonesia. The results demonstrate that there is a compelling economic case for cities in both developed and developing country contexts to invest, at scale, in cost-effective low-carbon measures. The results suggest that these investments could generate significant reductions (in the range of 15–24% relative to business-as-usual trends) in urban carbon emissions over the next 10 years. Securing these savings would require an average investment of $3.2 billion per city, which if spread over 10 years equates to 0.4–0.9% of city GDP per year. However, the savings generated in the form of reduced energy bills would be equivalent to between 1.7% and 9.5% of annual city-scale GDP, and the average payback period of investments would be approximately 2 years at commercial interest rates. We provisionally estimate that if these findings were replicated and similar investments were made in cities globally, then they could generate reductions equivalent to 10–18% of global energy-related GHG emissions in 2025. While the studies offer some grounds for optimism, they also raise important questions about the barriers to change that prevent these economically attractive options from being exploited and about the scope for mitigation based on the exploitation of only the economically attractive options. We therefore discuss the institutional capacities, policy environments and financing arrangements that need to be developed before even these economically attractive opportunities can be exploited. We also demonstrate that, in rapidly growing cities, the carbon savings from such investments could be quickly overwhelmed – in as little as 7 years – by the impacts of sustained population and economic growth. We conclude by highlighting the need to build capacities that enable the exploitation not only of the economically attractive options in the short term but also of those deeper and more structural changes that are likely to be needed in the longer term.

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1. Introduction

Of the 7.1 billion people alive today, more than 3.6 billion live in cities. By 2050 the urban population is predicted to pass 6.7 billion (UNDESA, 2014). Forecasts suggest that the vast majority of this urban population – some 5.2 billion people – will live in low- and middle-income countries, where the number of city-dwellers is increasing by 1.2 million people per week (WHO, 2014). Although the urban population in high-income countries is growing more slowly, it is still forecast that around 1.2 billion people will be living in cities in high-income countries by 2050 (WHO, 2014).

The rapidly growing significance of cities in the developing world, and their sustained importance in the developed world, has profound implications for the mitigation of climate change. Arguably, when compared to the body of research on international or national climate strategies, the body of research on the links between cities and greenhouse gas (GHG) emissions is relatively small. However, a growing number of studies have evaluated the emissions that can be directly attributed to different cities (cf. Brown et al., 2009; Dhakal, 2009; Glaeser and Kahn, 2010; Bi et al., 2011; Kennedy et al., 2012; Creutzig et al., 2015; Colenbrander et al., 2015a, 2015b). Other studies have considered the wider carbon footprint of the consumption that takes place in different cities (cf. Khan, 2012; Hoornweg et al., 2011; Feng et al., 2014).

There have also been various high-level assessments of urban energy use and of the carbon emissions that can be attributed to cities (cf. GEA, 2012; IEA, 2013a; IPCC, 2014). These assessments note that the estimates of urban energy use and emissions generated to date have often been based on different approaches that have been applied at different scales with varying assumptions and units of analysis. Various authors also note that are frequently issues with accessing robust and comparable data at the city scale (Brown et al., 2009; Dhakal, 2010; Weisz and Steinberger, 2010; Sovacool and Brown, 2010; Minx et al., 2013). Recent initiatives have sought to advance and standardize the ways in which urban GHG inventories are prepared. Informed by previous research such as Kennedy et al. (2011), the Global Protocol for Community Scale GHG Emission Inventories (the GPC) was launched in 2014 (GHG Protocol, 2014). The GPC is being adopted widely and is expected to underpin emerging initiatives such as the Compact of Mayors.

The IPCC has estimated that the fuel that is consumed and the other activities that take place within cities directly account for 44% of global GHG emissions (IPCC, 2014). However, when considering their final consumption of electricity and excluding non-CO_2 GHG emissions, the IPCC estimates that 71–76% of the global CO_2 emissions from final energy use can be attributed to cities (IPCC, 2014). Various analyses have suggested that when wider consumption-based impacts are taken into account the share of global energy-related CO_2 emissions attributable to cities would be higher (Satterthwaite, 2008; Khan, 2012; Hoornweg et al., 2011; GEA, 2012; Feng et al., 2014).

This has led some to suggest that it is not cities per se that are responsible for a high proportion of global emissions but the levels of economic activity and the numbers of affluent consumers that are often concentrated within them (Satterthwaite, 2008; Dodman, 2009; Hoornweg et al., 2011; Minx et al., 2013). However, others emphasize that urbanization offers opportunities to improve living standards while reducing the carbon intensity of development, particularly through more compact and energy efficient forms of development (cf. Khan, 2012; Weisz and Steinberger, 2010; Hoornweg et al., 2011; Feng et al., 2014; Floater et al., 2014; Creutzig et al., 2015). There is therefore a need for a nuanced attribution of energy consumption and GHG emissions to cities and the activities that take place and the people that live within them, and of the opportunities that different forms of urban development offer for climate change mitigation (Sovacool and Brown, 2010; Weisz and Steinberger, 2010; Hoornweg et al., 2011).

Despite the on-going debates and the remaining uncertainties, it is widely accepted that the urban development decisions taken in the next few years will be crucial in determining the success of global climate mitigation efforts. This has fuelled research on the drivers of urban energy use and carbon emissions, and the associated scope for climate mitigation. A summary of the key factors that emerge from the wider literature is presented in Table 1.

Although the studies cited in Table 1 have considered the broad mitigation potential in key sectors in cities, as yet there have been no analyses of the economics of low carbon urban development the economic case for investment in low carbon urban development on a measure-by-measure basis. Of course, there have been various estimates of global investment needs relating to low-carbon development (Stern, 2007; GEA, 2012; WEF, 2013; McCollum et al., 2013; IEA, 2013a), and it can be assumed that a considerable proportion of these investment needs will occur in cities. There have also been estimates of the low-carbon investment needs in specific areas such as infrastructure (Kennedy and Corfee-Morlot, 2013) or buildings (IEA, 2013b). But there have been very few assessments relating directly to the economic case for urban action on climate change.

This paper is based on the view that the lack of research on the economics of low-carbon cities is significant for several reasons.

1) Cities are the places where substantial sections of international and national climate policy ‘hit the ground’. Local authorities have critical powers with respect to climate mitigation, including land use planning, urban transport provision and the enforcement of energy regulation (Dodman, 2009). International bodies, national governments and local authorities therefore need to understand the opportunities in and priorities of cities if they are to design effective policies and develop the multi-level governance frameworks needed to deliver these.
2) Cities are distinguished by the concentration of social and economic activity that takes place within their boundaries. This means that local authorities have unique opportunities to deliver certain low-carbon measures in a cost-effective way (such as mass transit or district heating), and to encourage mass adoption of both technical and behavioural low-carbon options (Dodman, 2009). Identifying economically attractive options can facilitate these actions.
3) Many cities are showing leadership on climate change, for example by establishing more ambitious emission reduction targets than national governments. However, to overcome the barriers to or to secure the resources for action, decision-makers

Table 1
Key factors shaping urban carbon emissions.

- History and levels of lock-in to existing infrastructure
- Geography, climate and weather and resource endowments
- Levels, rates and forms of social and economic activity and growth
- Urban governance capacities and abilities to influence development patterns
- Levels of pressure and/or support from international and national policy
- Levels of access to finance and an ability to invest in infrastructure
- The carbon intensity of electricity supply and energy prices
- Urban form, land use mix and the extent of compact, connected development
- Levels and forms of transport demand and ease of access to public transport
- Buildings efficiency and levels of demand for heating and cooling
- Levels of income, forms of lifestyle and patterns of consumption

Sources: Brown et al. (2009), Kahn (2009), Kennedy et al. (2009), Weisz and Steinberger (2010), Glaeser and Kahn (2010), Sovacool and Brown (2010), GEA (2012), Mohareb and Kennedy (2012, 2014), Minx et al. (2013), Feng et al. (2014), Floater et al. (2014), Matsumoto et al. (2014), IPCC (2014) and Creutzig et al. (2015).

often require an economically compelling case for action. Presenting an economic case can change the political dynamics of climate action.

4) Local authorities and other decision makers need locally relevant evidence on the most carbon and cost-effective ways of delivering their climate targets. Studies of the economic case for low-carbon investment at the city scale can help to inform decision-making, and subsequently to secure the major investments necessary to meet their climate targets.

This paper responds to the gap in the literature by conducting a comparative analysis of five recently completed studies that assessed the potential for cost-effective investments in low-carbon measures in five cities: Leeds City Region in the United Kingdom, Johor Bahru (including Pasir Gudang) in Malaysia, Lima-Callao in Peru, Palembang in Indonesia and Kolkata in India (see Gouldson et al., 2012, 2014a, 2014b, 2014c, 2014d; Colenbrander et al., 2015a, 2015b). While these cities cannot be said to fully represent the variety of cities that exist today, they are geographically diverse, are found in high-income (the UK), upper middle-income (Malaysia and Peru) and lower middle-income (India and Indonesia) countries and are pursuing a range of development modes. The comparative analysis therefore illustrates a range of the different levels and trends in population and economic growth, energy consumption and carbon emissions that are likely to be found in many cities around the world.

The paper is structured as follows. Section 2 outlines the methodologies employed for the city studies and this comparative analysis. Section 3 presents and compares the headline findings from the five city studies, and seeks to contextualize the impact of investment in cost-effective low-carbon measures. Section 4 looks in more detail at each of the five cities, discussing the specific low-carbon opportunities available in each city. Section 5 considers the global implications of this research and identifies the capacities that need to be developed if the economically attractive options are to be widely exploited in a way that moves the city towards deeper decarbonization. Section 6 presents conclusions and offers two different scenarios for large-scale low-carbon investment in cities.

2. Methodology

The methodology used in each of the city studies includes three stages:

1) An assessment of recent trends in the city's energy use, energy expenditure and GHG emissions, and projection of these trends over the next decade (the business as usual (BAU) baselines);
2) An evaluation of the costs, benefits and carbon saving potential of a wide range of the low-carbon measures that could be adopted in different sectors in the city in the next decade; and
3) An aggregation of the findings and the presentation of the economic case for investment in these options at scale in different sectors in the city over the next decade.

This comparative analysis additionally includes a new calculation – the Time to Reach BAU Levels of Emissions (TREBLE) point – for different levels of low-carbon investment in each city. This is explained in detail below.

As is discussed below, Stage 1 of the methodology adopted many but not all of the elements of the new GPC (GHG Protocol, 2014). However, the issues with gaining access to suitably robust city-scale data that were raised above were apparent in each of the case study cities. In response, the studies adopted a form of iterated participatory appraisal (see Fraser et al., 2006). This approach was based on the collation of preliminary data from extensive reviews of academic literature, government publications and industry reports, and its presentation to project steering groups and stakeholder panels. These groups included representatives from national governments, city authorities, development agencies, industry groups, civil society organizations and local universities. The panels reviewed and refined the preliminary data to ensure its relevance to and accuracy in the local context, as well as assessing the methods, assumptions and outputs of the research. Full details of the steering groups and membership of the stakeholder panels are presented in the original city-reports and in related academic publications (see Gouldson et al., 2012, 2014a, 2014b, 2014c, 2014d; Colenbrander et al., 2015a, 2015b). Although this approach enabled the research to take place in a way that built confidence in and local ownership of the results, the scope and complexity of the research the steering groups and stakeholder panels were not able to discuss uncertainty ranges or confidence intervals for the data they helped to generate.

2.1. Setting the scope and boundaries of the city studies

Geographically, each study focused on a metropolitan area or city region with boundaries determined in conjunction with local authorities. This allowed us to consider energy use within the broader travel-to-work area that was under the influence of the metropolitan government.

Technically, in terms of carbon accounting, the baseline assessments in each of the studies considered GHG emissions from the metropolitan area, including those from direct consumption of fuels and waste management facilities within city boundaries (so-called Scope 1 emissions) and those produced by generating the electricity consumed within the city (Scope 2 emissions). Industrial process emissions, which fall within Scope 1, had to be excluded due to lack of data. Emissions to or from transport areas outside of the metropolitan travel-to-work area were also excluded, as were emissions from agriculture, forestry and land use. None of the studies considered embedded energy or carbon in the goods or services consumed within the city (Scope 3 emissions). The studies therefore focused primarily on territorial emissions within each city, with consumption-based emissions considered for electricity use only. Drawing on the review of accounting procedures for urban GHG emissions presented in Kennedy et al. (2011) and the recently published GPC (GHG Protocol, 2014), a summary of the technical scope of the emissions inventories, the baseline forecasts and the options appraisal stages is presented in Table 2.

Temporally, the studies focused on the medium term, basing BAU calculations on the last 10–15 years and assessing the impacts of adopting low-carbon options in the next 10 years. This timeframe helps to ensure that the findings are relevant to current decision-makers. Like Mohareb and Kennedy (2012), forecasts of future baselines were based on extrapolations of recent trends, although the timelines for this research ran to 2025 rather than to 2050. Given their short to medium term focus, the studies do not factor in any of the prospective impacts of technological learning (see below).

Economically, each study focused on the case for investing in specific low-carbon measures. They did not consider the potential of broader programmes (i.e. relating to the promotion of compact urban development) as an economic assessment of these would have required very different research methods to those used here (NCE, 2014). For the low-carbon measures that were included, the studies evaluated only the direct, private financial costs and benefits. Of course we recognize that any such measure could also have potentially significant social co-costs and co-benefits, for example in the form of distributional consequences, environmental impacts and wider economic multiplier effects. These are not formally considered in the quantitative analysis presented here.

Table 2
Scope of baseline inventories, BAU forecasts and measures appraisal.

	Electricity[a]	Transmission losses	Buildings energy use	Transport fuel use[b]	Aviation	Marine	Railways[b]	Biofuels	Industrial processes	Industrial energy use	AFOLU[c]	Waste[d]	Upstream fuels	Embodied carbon
Johor Bahru, Malaysia	B	B	B&M	B&M	–	–	B&M	B&M	–	B&M	–	B&M	–	–
Kolkata, India	B	B	B&M	B&M	–	–	B&M	B&M	–	B&M	–	B&M	–	–
Leeds, UK	B	B	B&M	B&M	–	–	B&M	B&M	–	B&M	–	–	–	–
Lima, Peru	B	B	B&M	B&M	–	–	B&M	B&M	–	B&M	–	B&M	–	–
Palembang, Indonesia	B	B	B&M	B&M	–	–	B&M	B&M	–	B&M	–	B&M	–	–

Source: Adapted from Kennedy et al. (2011) and GHG Protocol (2014).
Key:
B – included in the baseline inventory and the business as usual forecast.
M – included in the measures appraisal.
[a] The potential application of low carbon measures in the large-scale generators supplying electricity to the relevant national or regional grids was not considered. However, the potential for the adoption of small-scale renewables within the city was considered.
[b] For travel within the city only.
[c] Agriculture, forestry and land use.
[d] For solid waste management options, excluding waste water.

This is not meant to downplay their significance: the presence of co-benefits such as improved public health or employment creation would strengthen the case and the presence of co-costs such as deteriorated public health or induced skills shortages could weaken the case for investment in particular measures. Careful design and delivery will be needed to maximize co-benefits and minimize co-costs. However, the narrower analysis presented in the studies reflects the reality that often the direct private economic case has to be demonstrated before policy-makers can start to consider potential investments and their wider impacts.

2.2. Calculating business-as-usual trends

The studies first sought to map the levels and composition of energy supply and demand in each city between 2000 and 2014. This history was developed using activity data for the residential, commercial and public, industrial, transport and waste sectors. These assessments used a wide range of data such as energy sales by sector, rates of appliance ownership, floor space by type, fleet size by vehicle type and efficiency, mode share by transport type, average passenger kilometres, per capita waste production and waste composition and destination. Full details of the key variables by sector are presented in the Supplementary Material, and further information on city-specific data sources are presented in the reports for each city study and in related academic papers (Gouldson et al., 2012, 2014a, 2014b, 2014c, 2014d; Colenbrander et al., 2015a, 2015b).

The BAU baselines for 2015–2025 were based on an extrapolation of historical trends in activity data between 2000 and 2014. These projections took into consideration projected population growth and large-scale planned investments currently under construction in each city. Changing consumer behaviour and background improvements in energy efficiency were also implicitly included in the trends in activity data. The key assumption at the heart of the studies was that trends in the different cities would continue in the near future as they had in the recent past. As is widely recognized (cf. GEA, 2012), the urban future may not look like the urban past, but such assumptions are common in such as assessments of BAU trends, are more likely to hold in the near term than in the longer term and were necessary to make the analysis feasible.

Baseline estimates of GHG emissions and energy expenditure were based on activity data. When estimating emissions from electricity consumption, this analysis took into account the changing carbon intensity of electricity between 2000 and 2025 (including transmission and distribution losses) based on current infrastructure and planned investments in the grid supplying each city. Nominal energy prices between 2000 and 2014 were converted into real prices at 2014 levels using context-specific consumer price indices. Based on an assessment of recent trends, we assumed that energy prices are expected to rise 2% per year in real terms in Leeds, Lima and Kolkata, and 3% per year in Indonesia and Malaysia. All future activities were compared against these baselines.

2.3. Identifying and evaluating low-carbon options

Preliminary long lists of the low-carbon measures that could be adopted in the residential, commercial, industrial, transport were developed for each city. The waste sector was also included in all of the cities other than Leeds where it was deemed to be outside of the project scope. Reflecting the approach to iterated participatory appraisal outlined above, project steering groups and stakeholder panels in each city helped to turn the long lists into shortlists of those measures that were considered appropriate for local climates, cultures and socio-economic structures.

The performance of the shortlisted measures and the scope for deployment of all measures were then assessed, drawing on literature reviews and consultations with the stakeholder groups. Based on the revised figures that emerged from the consultations, capital costs, operating costs and estimates of the potential for deployment of each measure in the period to 2025 were combined to determine the net present value (NPV) of each measure. Similarly, the mitigation potential of each measure was based on calculations of the renewable energy generated, energy use avoided or the waste emissions prevented, compared with BAU levels. The preliminary figures were again reviewed and refined by stakeholder groups before being finalized.

The NPV calculation for each measure focused narrowly on direct private costs and benefits. The costs considered were the incremental costs of buying, installing and running the low-carbon measures when compared to the standard, higher-carbon equivalents that are commonly in place in each city. In each case we used a standard real interest rate of 5%, which was deemed by the project steering groups to be a realistic borrowing rate in each city after adjusting for inflation. In each case we also held the costs of measures constant at 2014 prices. In contrast to studies such as those conducted by Mohareb and Kennedy (2012, 2014), we did not consider the impact of technological learning on the cost and performance of measures. This makes our estimates of economic and environmental performance more conservative. Further detail on the specific costs, benefits and deployment rates of each measure in each city are fully detailed in Gouldson et al. (2012, 2014a, 2014b, 2014c, 2014d) and Colenbrander et al. (2015a, 2015b).

The estimates of NPV and carbon savings were then used to rank the measures in order of (i) the total carbon savings that they could generate to 2025 and (ii) the cost-effectiveness of these carbon savings, calculated by dividing the NPV of the measure over their lifetimes by the carbon savings through to 2025. Many of these measures will exist beyond 2025, therefore the lifetime carbon savings are likely to be higher than those reported here. These league tables indicate the potential impacts of deploying any individual measure independently, i.e. without relying on the adoption of any other measure. Short versions of the league tables for the five cities are included in the Supplementary Material.

The league tables contain equivalent information to that used as the basis for marginal abatement cost (MAC) curves. We present results in the form of league tables as steering groups and stakeholder panels generally deemed these to be more accessible and useful than MAC curves. However, we also present city-specific MAC curves in the Supplementary Material. MAC curves have been criticized because they fail to consider cost uncertainties, interactions between measures, unintended consequences and transaction and policy implementation costs (IPCC, 2007; Kesicki and Ekins, 2012; Vogt-Schilb and Hallegate, 2014). However, in our analysis, cost uncertainties were addressed both through the selection of conservative figures and the participatory review processes outlined above. While the league tables do not account for interactions between measures, we explore these impacts on the net financial and carbon savings in the investment scenarios (see Section 2.4). By considering not only purchase but also installation and maintenance costs for each measure we also considered some of the key transactions costs that are often left out of the data underpinning MAC curves. However, our focus only on the direct costs and benefits of different measures meant that the analysis does not consider potential unintended consequences or policy implementation costs. Although we argue that the outputs of our analysis have value as they help analysts and decision makers to understand the scope for climate action at the city scale and to quantify and rank the different low-carbon measures available, we do not claim that the data presented are complete, robust or detailed enough to underpin, for example, specific investment decisions.

2.4. Calculating potential savings at the city scale

Two aggregated scenarios were then developed based on the assessment of the measures and the league tables of their cost and carbon effectiveness. In the first scenario, the cost-effective measures are deployed. Where two measures were mutually exclusive or where interactions led to individual measures no longer presenting a positive economic case, the more economically attractive measure was included in the scenario. In the second scenario, it was assumed that the returns from the cost-effective scenario would be reinvested in those measures that do not independently have a positive net present value. This produced a "cost-neutral" bundle of measures that could be adopted at no net cost on commercial terms over all of the measures' lifetimes. These bundles therefore included the economic and carbon savings that could be realized if the returns from the cost-effective measures were recycled and re-invested in further low-carbon measures. While this analysis considers costs and benefits across the city as a whole, with the city itself being seen as the functioning economic unit, it should be noted that cost-recovery mechanisms would need to be in place for financial savings from cost-effective low-carbon measures to be captured and re-invested. This scenario should therefore be viewed as highly theoretical.

When developing these scenarios, it is important to highlight that the performance of a measure depends on whether, and to what extent, other options are deployed (Bajželj et al., 2013). For example, when adopting mandatory energy performance standards for air conditioners, we assume that the introduction of green building standards has already reduced the need for air conditioning and the savings from more energy efficient air conditioners. While the league tables assess the performance of measures deployed individually, as outlined above, we accounted for these kinds of interactions between measures when developing scenarios to better illustrate potential city-scale financial and carbon savings.

2.5. The TREBLE point

The significance of the rebound effect – where additional energy consumption is enabled by improved energy efficiency (Madlener and Alcott, 2009) – is widely acknowledged. Berkhout et al. (2000) estimate that, although they vary by measure, rebound effects reduce the savings from energy efficiency measures by between 0% and 15%, while Hertwich (2005) and Sorrell et al. (2009) suggest that rebound effects, although variable are typically less than 30%. It therefore seems likely that the energy and hence the cost and carbon savings predicted above could be reduced by rebound effects. As there are multiple components and systemic dimensions to rebound effects, and as such effects are often specific to both an individual measure and to the context of its application, we judged that a calculation of the rebound effects that are likely to be experienced in each of the case study cities was outside the scope of this paper. Instead, we highlight the time it would take for continued urban growth – even in a more energy efficient and lower carbon form – to cancel out the savings made through the investments in the low-carbon measures that are the main focus of the paper.

To do this, we propose the concept of the TREBLE point. The TREBLE point compares the time taken for emissions *with* investment in low-carbon measures to reach the level that would have been realized *without* such investment under the BAU scenario in a reference year, in this case 2025. A positive number suggests that with investment the BAU level of emissions forecast for 2025 would still be realized but a number of years later; a negative number suggests that the BAU level of emissions forecast for 2025 would be realized a number of years earlier. If emissions after investments are unlikely to reach the BAU reference point in the foreseeable future, there is no TREBLE point.

In calculating TREBLE points for the cost-effective and cost-neutral scenarios for each city, we have assumed that the cities maintain the lower-carbon intensity of growth that comes with investment in low-carbon measures. This is plausible given the long lifespan of many options, such as green building standards, mandatory energy performance standards and public transport infrastructure. Given the rapid accumulation and long life of carbon in the earth's atmosphere, the immediate carbon savings from these investments are important in themselves. However, the analytical value of the TREBLE point lies in revealing the amount of time that a particular low-carbon investment can gain for a city seeking overall and permanent emission reductions in the context of on-going growth.

3. Results

3.1. Business-as-usual trends

BAU baselines for economic development, energy consumption, emissions intensity of economic activity and total carbon emissions for each of the five cities are presented in Fig. 1. The averages for member countries of the Organization for Economic Co-operation and Development (OECD) are also shown for reference. According to our BAU projections, in the period from 2014 to 2025:

- Average per capita energy consumption will rise significantly in Johor Bahru and Palembang, driven by industrial expansion, and rise slightly in Kolkata, Lima and Leeds. All cities will remain significantly below OECD averages.
- Average per capita emissions will continue to rise in all cities except Leeds, where it will fall markedly in line with OECD trends. Emissions per capita in Johor Bahru will exceed the average in OECD countries.
- The emissions intensity of economic activity will fall in all cities except Palembang, where fuel switching to more carbon-intensive energy sources is anticipated.

Putting these baselines together reveals the trajectories for absolute emissions levels in each city between 2014 and 2025 under BAU conditions. Absolute carbon emissions will increase in the four developing world cities: by 54% in Kolkata, 52% in Lima, 84% in Johor Bahru and 165% in Palembang. In Leeds, however, they will fall by 13%.

More detail about relevant developments in each city is given in the case studies in Section 4.

3.2. Comparing the economic cases for low-carbon investment in the five cities

In contrast to the BAU scenarios, the economic cases for low-carbon investment in the five cities show some striking similarities. The summary results of the economic analysis for investments

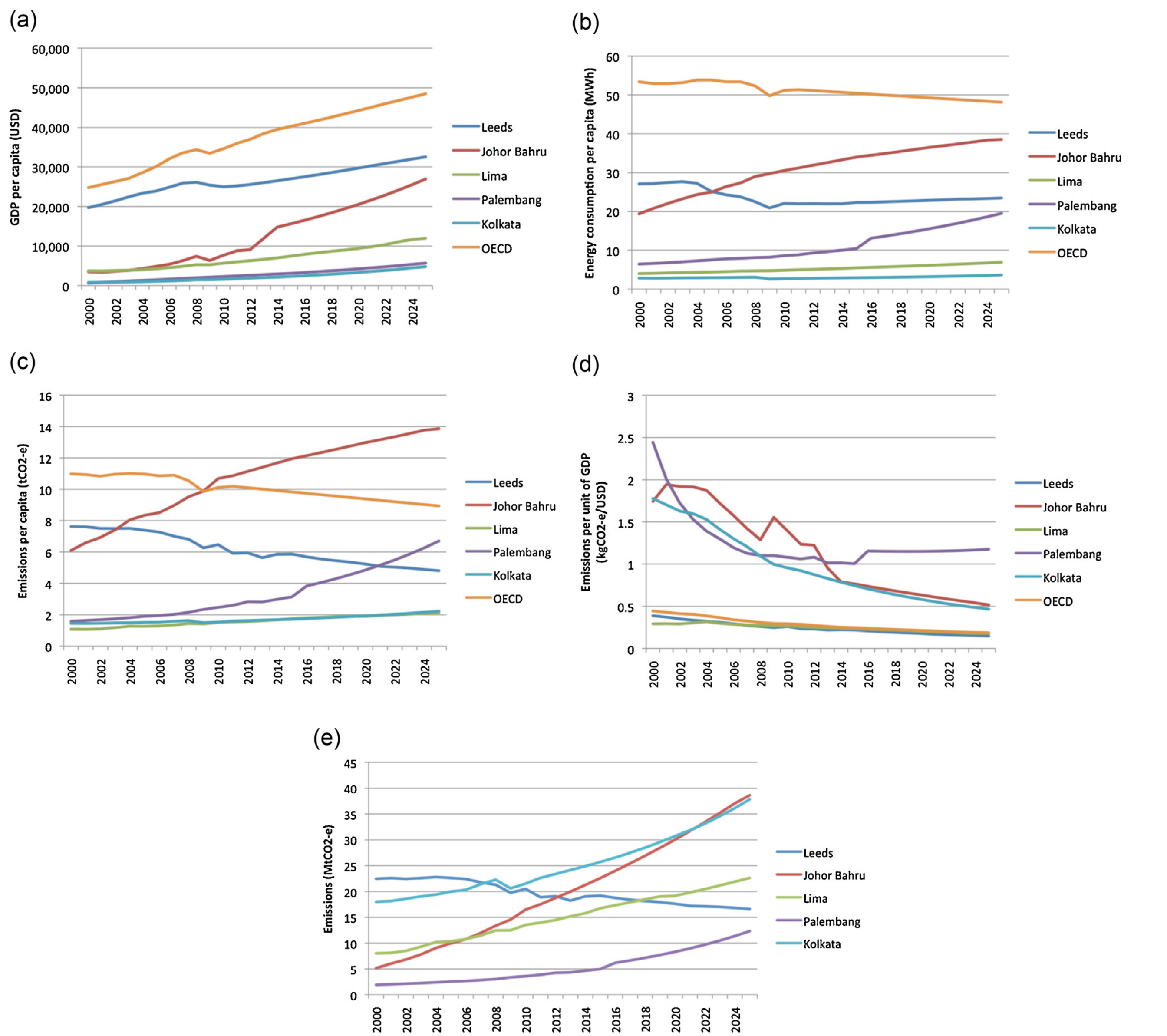

Fig. 1. Business-as-usual baselines for the five cities. (a) GDP per capita 2000–2025. (b) Energy consumption per capita 2000–2025. (c) Emissions per capita 2000–2025. (d) Emissions per unit of GDP 2000–2025. (e) Total emissions 2000–2025.

Table 3
Summary of the estimated costs and benefits of two levels of low-carbon investment in the five cities.

	Leeds	Johor Bahru	Lima	Palembang	Kolkata
Cost-effective scenario					
Investment needs (US$ billion)	7.7	1.0	5.0	0.4	2.0
Investment needs (% of city GDP)	8.9	3.7	7.5	8.8	6.3
Annual savings (US$ billion)	1.9	0.8	2.1	0.4	0.5
Annual savings (% of city GDP)	2.2	2.9	3.2	9.5	1.7
Payback period (years)	4.1	1.3	2.4	<1	3.9
Carbon savings in 2025 ($MtCO_2$-e)	2.6	9.4	3.5	3.2	7.8
Carbon savings in 2025 (% of BAU)	15.6	24.2	14.7	24.1	20.7
TREBLE point (years)[a]	−6	11	7	8	15
Cost-neutral scenario					
Investment needs (US$ billion)	18.1	5.6	10.8	1.5	3.6
Investment needs (% of city GDP)	21	20.8	16.3	33.6	11.4
Annual savings (US$ billion)	2.5	0.8	2.4	0.5	0.6
Annual savings (% of city GDP)	2.9	3.1	3.6	10.2	1.8
Payback period (years)	7.3	6.8	4.5	3.3	6.2
Carbon savings in 2025 ($MtCO_2$-e)	3.6	17.5	5.2	3.7	13.6
Carbon savings in 2025 (% of BAU)	21.8	45.4	22.4	28.3	35.9
TREBLE point (years)[a]	−7	NA	15	10	NA

[a] Time to Regain BAU Levels of Emissions: the number of years earlier or later that a city reaches the BAU level of emissions it would have had in 2025, due to the emission reductions from low-carbon investments. A positive value indicates that anticipated emissions growth has been pushed back. A negative value indicates that anticipated emission reductions have been brought forward. NA indicates that emissions levels after low-carbon investment do not regain the levels projected under BAU conditions for the foreseeable future.

in cost-effective and cost-neutral bundles of measures are presented in Table 3.

These results suggest that there are very significant opportunities for cities to exploit economically attractive initiatives that would cut their carbon emissions. The package of cost-effective investments would pay for themselves through the energy that they save quickly, in one case in a matter of a few months, and relative to BAU trends they would generate carbon savings in the range of 15–24% by 2025. As most of the low-carbon measures considered have lifespans beyond their payback periods, the investments made would carry on generating both financial and carbon savings over a much longer period.

If the savings from these cost-effective investments were captured and reinvested in further low-carbon measures up to the point where all investments would be cost-neutral then levels of investment would at least double in most of the cities. While the payback periods of these cost-neutral bundles of investments would be longer – up to 8 years – by 2025 they could reduce emissions by 22–45% relative to BAU trends.

3.3. TREBLE points: the impacts in a longer-term perspective

Analysis of the TREBLE points reveals that with cost-effective investments, the four developing world cities could keep emissions below the BAU levels projected for 2025 for a further 7–15 years (see Fig. 2 and Table 1). However, the analysis also shows that the impacts of sustained population and economic growth would then more than offset these improvements. For the Leeds City Region, where BAU levels of emissions are falling, investing in the cost-effective options could bring the reduced BAU level of emissions projected for 2025 forward by as much as 6 years.

The prospects for cost-neutral levels of investment to reduce overall emissions in the longer-term are even more compelling. In the cost-neutral scenarios, Palembang would keep emissions levels below the BAU level projected for 2025 for 10 years and Lima for 15 years. In Johor Bahru and Kolkata, there is no TREBLE point in the cost-neutral scenario: in other words, if the impact of the cost-neutral bundle of measures is sustained, these cities could effectively shift to low-carbon development trajectories at no net cost. This is an even more substantial contribution, as it suggests that, in some cities at least, economically neutral levels of low-carbon investments could have long-term impacts on carbon emissions.

It is worth emphasizing that the emission reductions from these low-carbon investments represent a substantial contribution to climate mitigation. With the exploitation of all cost-effective low-carbon measures, the five cities could avoid emissions of between 2.6 and 9.4 $MtCO_2$; with the further deployment of all cost-neutral options, the five cities could avoid emissions of between 3.6 and 17.5 $MtCO_2$-e (see Table 3 and Fig. 2). While these are very significant reductions in carbon emissions, the analysis of TREBLE points makes it clear that cities cannot deliver sustained emission reductions by only exploiting economically attractive options. It will be necessary to invest in less economically attractive options, and possibly wider and deeper changes in urban form and function, if growing cities want to achieve deeper cuts in their carbon emissions in the longer-term.

3.4. Global implications

This comparative analysis indicates that there is scope for economically attractive investments to reduce energy use, energy bills and carbon emissions, relative to BAU trends, in diverse cities at different stages of development. Of course, the small sample of cities examined here is unlikely to be representative of the wider range of cities and the multiple factors shaping their carbon emissions. However, if the opportunities available to the five case study cities were broadly representative, and all cities were to identify and exploit similar opportunities, then this would lead to very substantial investments in the low-carbon economy and reductions in carbon emissions that would be significant at the global scale.

As a very broad and very preliminary estimate, if 71–76% of global energy-related GHG emissions come from cities (IPCC, 2014), and cities could be reduce their GHG emissions by 15–24% through cost-effective investments (as in our small sample), then very cautiously we could estimate that cities could achieve reductions equivalent to 10–18% of global energy-related emissions in 2025. Further, if GHG reductions of 22–45% are available through cost-neutral levels of investment in all cities, then – equally cautiously – we could estimate that cities could deliver carbon savings equivalent to 15–34% of global energy-related emissions at no net cost.

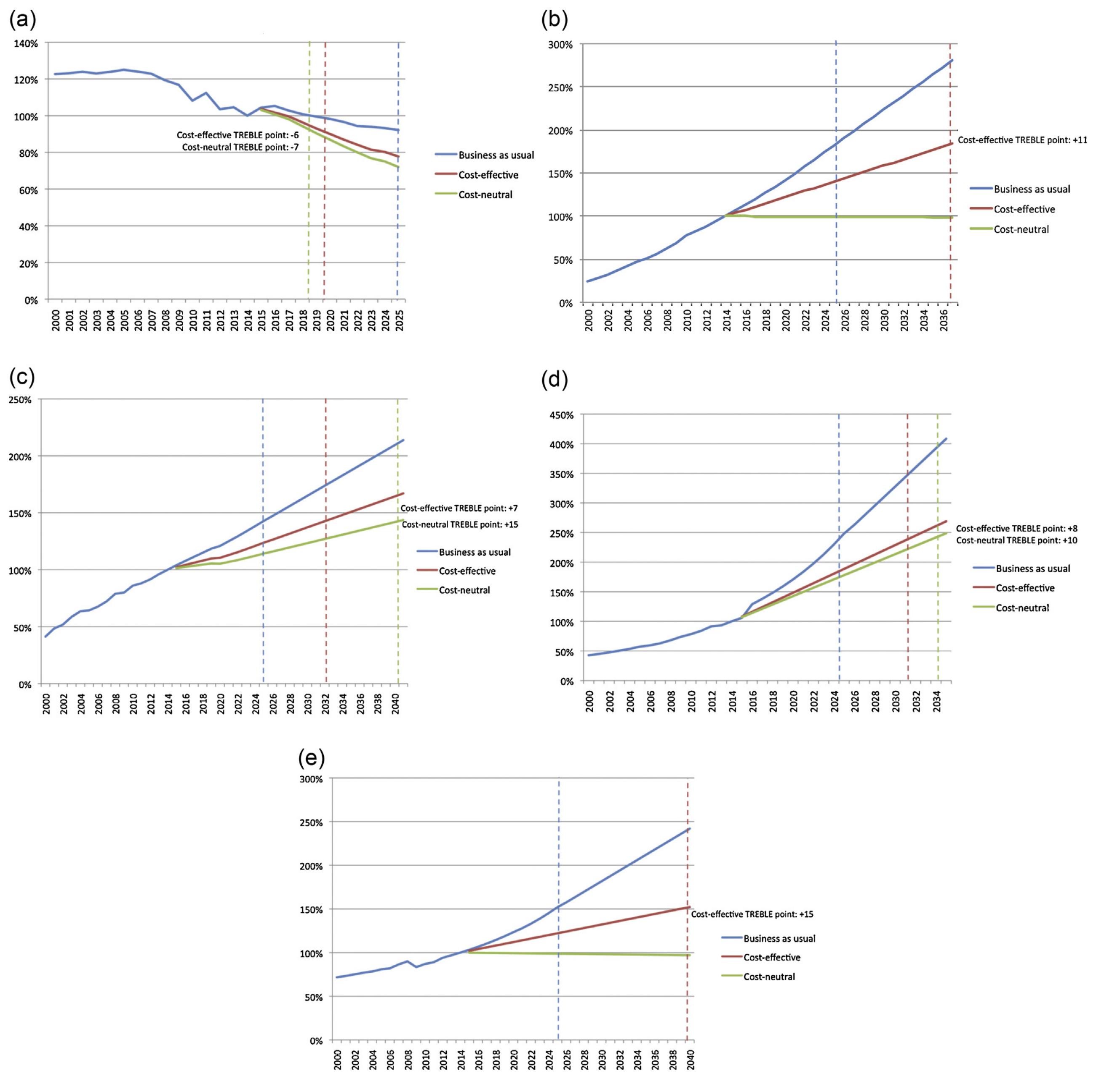

Fig. 2. Impacts of cost-effective and cost-neutral levels of investment on BAU trends in the five case study cities, with analysis of TREBLE points. (a) The Leeds City Region. (b) Johor Bahru. (c) Lima-Callao. (d) Palembang. (e) Kolkata.

4. Case studies

This section provides more detail about each of the five cities studied. We present the broader context of the city to illustrate its relative carbon intensity and development level, and explore the economic and carbon savings of deploying the cost-effective and cost-neutral bundles of low-carbon measures. Each case study also zeroes in on a particular sector where the most interesting opportunities can be found in that city. Summaries of key data and findings for each city can be found in the Supplementary Material.

4.1. The Leeds City Region, UK

The Leeds City Region – that includes the local authority districts of Barnsley, Bradford, Calderdale, Craven, Harrogate, Kirklees, Leeds, Selby, Wakefield and York – has a population of over three million and an economy worth over £52 billion (US$86.2 billion), approximately 5% of the UK economy. Per capita GDP in the area is approximately £17,000 (US$26,500) and per capita energy consumption is 75% of the OECD average. The carbon intensity of electricity is 0.27 tCO_2-e/MWh but this figure is falling as less carbon-intensive electricity sources come online. The city region's aggregate energy use is relatively stable, but its annual energy bill of £5.4 billion (US$8.4 billion) – approximately 10% of city GDP – is steadily increasing.

The Leeds City Region faces many of the energy and carbon challenges of other established cities in the developed world. It has a largely de-industrialized, service-based economy with relatively high levels of wealth, energy consumption and carbon emissions when compared to world averages. Its infrastructure is extensive but relatively old, and may need to be substantially retrofitted to reduce emissions intensity. Transitioning to a low-carbon city will therefore demand substantial investment, although ongoing decarbonization of electricity supply at the national scale means that the city's annual emissions are falling in absolute terms.

We find potential for £4.9 billion (US$7.7 billion) of cost-effective investments in different energy efficiency, renewable energy and other low-carbon measures within Leeds. These would generate annual savings of £1.2 billion (US$1.9 billion), meaning that they could pay for themselves in around 4 years. If these investments were made, we estimate that Leeds could reduce its annual carbon emissions by 2025 by 16%, relative to BAU levels. The emission savings would be distributed among the commercial (30%), domestic (29%), industrial (33%) and transport (7%) sectors. A cost-neutral package of measures would mobilize £11.6 billion (US$18.1 billion) of low-carbon investments and would deliver annual emission reductions of 22% in 2025 relative to BAU levels at no net cost to the city.

Much of the carbon saving potential is found in the domestic sector. Much of the housing stock in Leeds was built before 1920, and is poorly insulated and energy inefficient and there is also some potential for the deployment of small-scale renewables.

Mini-wind turbines with a feed-in tariff, for example, have an economic value of £467 (US$729)/t$CO_2$ measure, although the scope for their deployment and hence their aggregate carbon saving potential is comparatively small. Biomass boilers with a renewable heat incentive are the next most cost-effective measure for the sector at £325 (US$507)/t$CO_2$ and also because of their widespread scope for deployment that offer large potential carbon savings. Reducing household heating levels by 1 °C could avoid 201 ktCO_2 cost-effectively, while solid wall insulation would save a further 198 ktCO_2 and could be included in a cost-neutral bundle of measures if it was cross-subsidized by the cost-effective low-carbon measures.

4.2. Johor Bahru, Malaysia

Johor Bahru, which for the purposes of the research here includes Pasir Gudang – is the third largest city in Malaysia, and serves as an important industrial, logistics and commercial centre. The population is currently 1.5 million but is expected to grow to 2.8 million by 2025. Massive additional investment in urban infrastructure and industrial development is planned over the next decade in order to meet the needs of the growing population and diversifying economy.

The city enjoys high growth rates after becoming the focus of Iskandar Malaysia regional economic corridor. Per capita incomes in the area are 48,880 Malaysian ringgit (MYR; US$14,790) and per capita energy consumption is 70.2% of the OECD average in 2014. These relatively high levels of energy use are unsurprising considering the city's large industrial base which includes oil refining and rubber processing. Further economic and population growth will see substantial increases in absolute levels of emissions (84%), energy use (79%) and energy bills (140%) in Johor Bahru over the period 2014–2025.

We estimate that Johor Bahru could reduce its carbon emissions by 24% in 2025, relative to BAU trends, through cost-effective investments worth MYR3.3 billion (US$1.0 billion). These would generate annual savings of MYR2.6 billion (US$0.77 billion), with the emission reductions distributed among the commercial (1%), domestic (20%), industrial (18%), transport (52%) and waste (9%) sectors. Reinvesting the returns on these investments in other low-carbon measures could enable investment in a cost-neutral package of measures worth MYR18.5 billion (US$5.6 billion), which would deliver emissions reductions of 45% relative to BAU at no net cost to the city.

Many of these low-carbon measures are found in the industrial sector. The petroleum refinery and petrochemical industry in particular could benefit from more efficient pumps, compressors, furnaces, boilers, heat exchangers and utilities. These are all cost-effective options, with an average value of MYR252 (US$76)/t$CO_2$-e and collectively able to save 4.4 MtCO_2-e by 2025. The rubber industry also offers several low-carbon measures that entail only small additional operational costs in return for large energy and carbon savings. Leak prevention and lowering functional pressure in boilers, for instance, could reduce emissions by an estimated 9.7 MtCO_2-e by 2025. The transport sector also contains a number of highly cost effective measures, the adoption of Euro IV vehicle standards for example could save 9.1 MtCO_2-e by 2025 and substantial savings could also be made through vehicle fuel switching and the diffusion of hybrid vehicles.

4.3. Lima-Callao, Peru

With a population of 9.2 million, Lima Metropolitan Area which includes both Lima and Callao is the fifth largest city in South America and by far the largest metropolitan area in Peru, accounting for 51% of national GDP and 84% of the tax base (INEI, n.d.). While Lima's GDP per capita reached approximately 18,590 Peruvian Nuevo Sol (PEN; US$6990) in 2014, provision of housing, transport and sanitation infrastructure has not kept pace with the increasing population. Absolute poverty in the city fell from 44.8% in 2004 to 15.7% in 2011, but approximately one in ten people continues to lack access to water and electricity (Sedepal, 2010). There has also been a substantial expansion of informal settlements on the periphery of the city.

Lima possesses a distinct advantage in the shift towards a low-carbon economy because of the availability of low-cost, low-carbon (0.24 tCO_2-e/MWh) electricity, largely generated from hydropower and natural gas, and because of a climate in which neither heating nor air conditioning are widely required. Projected BAU trends suggest that, while energy consumption per capita grew 32% between 2000 and 2014, current levels are only 10% of the OECD average. However, economic development and a growing population will see substantial increases in absolute levels of emissions (52%), energy use (48%) and energy bills (92%) in Lima between 2014 and 2025.

We estimate that, compared to BAU trends, Lima could reduce its carbon emissions by 2025 by 15% through cost-effective investments of PEN13.2 billion (US$5.1 billion). These investments would generate savings of PEN5.5 billion (US$2.1 billion), with the emission reductions distributed among the commercial (10%), domestic (15%), industrial (24%), transport (42%) and waste (8%) sectors. We calculate that reinvesting the returns from these investments in other low-carbon measures would enable an extra PEN19.7 billion (US$7.1 billion) of investments that would deliver emission reductions of 22% relative to BAU levels at no net cost to the city.

Many of the low-carbon measures available in Lima would have significant social and environmental co-benefits, particularly with respect to the city's congested transport infrastructure. Improving the energy efficiency of informal public transport networks is one commercially attractive intervention. Combis (large, privately-owned minibuses) accommodated approximately 20% of trips in Lima in 2014. Our analysis suggests that replacing these with modern buses would require an investment of PEN978 million (US$372 million) and yield carbon savings of 357 ktCO_2 in 2025. Congestion tolls in city centres are also attractive to urban planners because they raise funds for public transport investments as well as reducing congestion. Although politically contentious, this policy could reduce emissions by over 400 ktCO_2 in 2025 while generating returns of PEN4340 (US$154)/t$CO_2$.

4.4. Palembang, Indonesia

Palembang is the seventh largest city in Indonesia, the capital and major industrial centre of the state of South Sumatra, and an important port for the island of Sumatra. The population of 1.5 million has an average income of 34.6 million Indonesian rupiah (IDR; US$2940) and consumes 30% of the OECD average per capita energy consumption. The carbon intensity of electricity supply is projected to rise from 0.84 tCO_2-e/MWh in 2014 to 0.94 tCO_2-e/MWh in 2025 as new coal-fired power plants come online. The large industrial base combined with the rising carbon intensity of electricity mean that Palembang has an increasingly energy- and carbon-intensive economy.

Energy use in the city has doubled since 2000, and is projected to more than double again between 2014 and 2025. A substantial expansion of electricity generation is required to meet new demand. The current energy bill for the city is IDR10.1 trillion (US$857 million) or 18.7% of GDP. Total expenditure on energy is projected to rise 155% by 2025, while carbon emissions are projected to increase by 165% over the same period with the large jump in emissions partly attributable to the construction of a large fertilizer factory within the city boundaries.

We estimate that Palembang could reduce its carbon emissions in 2025 by 24%, compared to BAU levels, through cost-effective measures. This would require investment of IDR4.8 trillion (US$405.6 million), which would pay for itself within a year through annual savings of IDR5.1 trillion (US$436.8 million). The carbon savings would be distributed among the commercial (1%), domestic (24%), industry (51%), transport (9%) and waste (15%) sectors. We calculate that reinvesting the returns from these investments in other low-carbon measures would enable a total investment of IDR18.2 trillion (US$1.5 billion) and would deliver emission reductions of 28% relative to BAU levels at no net cost to the city.

The provision of reliable, low-carbon electricity would substantially expand the emission reduction measures available to Palembang and other Indonesian cities. Our analysis identifies two cost- and carbon-effectives measures available to the Sumatran grid. 514 MW of existing natural gas generation capacity could be retrofitted with best available technologies at a return of IDR745,193 (US$62)/$tCO_2$, and some 1200 MW of geothermal generation capacity could be built instead of coal-fired power plants with a return of INR95,712 (US$8)/$tCO_2$. These measures would save 38.6 $MtCO_2$ by 2025.

4.5. Kolkata, India

Kolkata is the third largest and the most densely populated city in India and the 19th largest urban area in the world (Government of West Bengal, 2009). Its official population of 14.1 million is currently growing at a rate of 6.9% per year (Government of India, 2011), but its unofficial population could be much larger. Electricity supply to the city comes largely from the West Bengal grid. Inefficiencies and losses in this grid mean that the electricity consumed in Kolkata has a carbon intensity of 1.52 tCO_2-e/MWh, more than double global best practice for low-grade, non-coking coal (IEA, 2010).

Average per capita income in Kolkata is 125,109 Indian rupees (INR; US$2139) and average annual per capita energy consumption is 3.6 MWh (7% of the OECD average). There are stark inequalities within the city. More than a third of Kolkata's population lives in slums, where most people work in informal sectors and a third are unemployed (UN Habitat, 2003). Even so, electricity demand is growing rapidly. We estimate that, under BAU conditions, Kolkata's total energy consumption would rise by 44%, expenditure on energy by 112% and carbon emissions by 54% between 2014 and 2025.

We estimate that Kolkata could reduce its annual carbon emissions by 21% by 2025, relative to BAU levels, through cost-effective investments of INR119.3 billion (US$2.0 billion). These would pay for themselves through annual savings of INR 30.4 billion (US$520.7 million) within 3.9 years, and then continue to generate savings for the lifetime of the measures. The carbon savings would be distributed among the commercial (25%), domestic (28%), industry (15%), transport (9%), and waste (23%) sectors. By reinvesting the returns from these cost-effective options, Kolkata could invest a total of INR205.6 billion (US$3.6 billion) in low-carbon measures and reduce its carbon emissions by 36% relative to BAU trends at no net cost to the city.

Kolkata's waste sector highlights the importance of evaluating the social and environmental implications of low-carbon measures, as well as the economic case for investment. Poor waste management impacts public health in the city, but also provides important sources of informal employment to some of the most vulnerable populations in the city. Any low-carbon measures need to capture potential health benefits while protecting these livelihoods. A community-led recycling scheme might therefore provide one option, reducing emissions by 226 $ktCO_2$-e. Gasification is also economically attractive, yielding INR135 (US$2)/$tCO_2$-e that could cross-subsidize investment in energy-from-waste infrastructure. These measures have the potential to yield a double dividend by displacing grid electricity generated from coal, thereby avoiding 2.8 $MtCO_2$-e by 2025.

5. Discussion

These findings reinforce the widely made claims about the significance of cities in climate mitigation, and particularly the importance of rapidly growing cities in middle-income countries (GEA, 2012; IPCC, 2014). The analysis highlights the consequences of 'business as usual' development in these cities, with carbon emissions forecast to increase by 52–164% in the next decade if the cities grow at the same rates and in the same ways as they have since 2000. The largest absolute and relative growth in emissions is seen in more industrial cities such as Johor Bahru in Malaysia and Palembang in Indonesia, compared to service-sector intensive cities such as Leeds in the UK or Lima in Peru. This highlights the importance of a consumption-based approach to urban GHG accounting, such as that adopted by Khan (2012), Hoornweg et al. (2011) or Feng et al. (2014). The application of a consumption-based approach would decrease the emissions attributed to 'producer' cities and increase them for 'consumer' cities (Satterthwaite, 2008; Hoornweg et al., 2011; GEA, 2012). As far as we are aware, the implications of such an approach for the selection of urban mitigation options have yet to be evaluated.

But the major finding of the analysis is that there is a compelling economic case for low-carbon investment in each of the five case study cities. The analysis shows that, over the next 10 years, annual investments of 0.4–0.9% of city-scale GDP would be needed to exploit these cost-effective opportunities, but that these measures would pay for themselves in c. 4 years through reductions in energy bills that would be equivalent to between 1.7% and 9.5% of annual city-scale GDP. The measures would continue to generate economic savings beyond the payback period and over their lifetimes. The analysis also finds that investments in these measures would reduce emissions from each city by between 15% and 24% relative to BAU trends by 2025, which equates to real annual carbon savings of between 3.2 and 9.4 $MtCO_2$-e in 2025. Furthermore, if the returns from the cost-effective options could be recovered and reinvested in additional low-carbon measures, these five cities could reduce their emissions by a further 3%-21% relative to BAU levels in 2025. This equates to another 0.5–8.7 $MtCO_2$-e. If all cities could identify and exploit similar opportunities for economically attractive low-carbon investment, the annual estimated emissions reduction – equivalent to 10–18% of global energy-related carbon emissions – would be a very significant contribution to climate change mitigation.

When expressed as a share of GDP, the city-level investment needs identified above are slightly lower than those identified at the global level by Stern (2007) and others. This is at least partly due to the narrower focus of our analysis on currently available mitigation options and the exclusion of other costs, relating for example to the costs of low carbon R&D or the need for investment in resilience and adaptation. More broadly, although Stern (2007) illuminated the broader longer-term economic logic for addressing climate change at the global scale, it is not always clear that this logic holds for specific investment decisions at the local level. The findings presented here provide an important complement to such analyses by demonstrating that investment in the early stages of the low-carbon transition could appeal to local decision makers and investors on direct, short-term economic grounds. This in turn indicates that climate mitigation ought to feature prominently in economic development strategies as well as in the environment and sustainability strategies that are often more peripheral to, and less influential in, city-scale decision making.

There are many reasons that cities have not exploited these substantial economic opportunities. ESMAP (2012, p. 3) states that 'Cities face major barriers to implementing sustainable energy measures. Even where there is a desire to improve their efficiency levels, cities often lack the requisite information, supportive national-level policies, access to financing and other support. City managers and mayors are often not equipped with adequate information or resources to identify and prioritize energy actions'. The IPCC (2014, p. 928) similarly states that cities need to develop institutional arrangements that facilitate the integration of mitigation with other high-priority urban agendas, a multi-level governance context that empowers cities to promote urban transformations and sufficient financial flows and incentives to adequately support mitigation strategies.

The presence of an economic case for low-carbon investment in cities could encourage city-leaders to build the relevant capacities and 'mainstream' climate change into core policy areas such as planning, economic development, infrastructure, transport and housing. The importance of such climate policy integration has been widely recognized at the national level (Jordan and Lenschow, 2010; Adelle and Russell, 2013) but research on this theme rarely considers the urban level.

While the economic case might capture the interest of decision-makers, in absolute terms the financial needs identified for each of the case study cities are very substantial, particularly relative to city budgets. However, it is important to recognize that many of the opportunities could be sufficiently economically attractive to take place without government support, and many of the other options could be promoted through policy rather than funded by government (see Colenbrander et al., 2015a, 2015b). As has been widely discussed, government policy can incentivize low-carbon investment through feed-in-tariffs or the removal of subsidies for fossil fuels. It can also enable actors to respond to market opportunities and policy signals through information provision, for instance by environmental labelling, or through support for R&D. And ultimately, it can mandate investment through regulation – for example through the adoption of tougher vehicle emissions standards or building energy performance standards.

Given the range of low-carbon measures identified in the five cities, it is clear that such policy interventions are likely to be needed both across levels (national, regional and local) and between policy areas (energy, finance, housing, transport and economic development, as well as environment). The need for effective multi-level governance arrangements to help cities respond to climate change is widely recognized (Betsil and Bulkely, 2006; Corfee-Morlot et al., 2009; Franzén, 2013; Acuto, 2013; Matsumoto et al., 2014). However, as NCE (2015) recognize, the details of such arrangements are often under-developed and cities are frequently constrained in their ability to pursue low-carbon development paths. This suggests that climate change needs to be mainstreamed by all actors and supported by vertical learning networks across scales horizontal learning networks between cities.

The potential for horizontal learning between cities is clear. Although there are some significant differences between the cities, relating for example to the carbon intensity of electricity supply or the levels of demand for heating and cooling, there are also some notable similarities. Each of the cities for example could exploit low-carbon options relating to green building standards and buildings retrofit and the adoption of more efficient modes of transport. And many of the governance challenges experienced by the different cities are also very similar. The scope for learning between cities – even when they are very different – is therefore readily apparent. We argue that the prospects for such learning are likely to be stronger where a compelling economic case has been put forward.

In the longer-term, the positive TREBLE point for each developing country city has shown that the emission reductions from the cost-effective options are likely to be overwhelmed by the impacts of ongoing economic and population growth. The analysis therefore clearly shows that cities cannot transition on to low-carbon development paths just by exploiting economically attractive low-carbon measures. In order to deliver sustained cuts in carbon emissions, cities would have to explore deeper and more structural forms of decarbonization that may not be as economically attractive (at least not on direct economic terms in the short to medium term) and that may also be more challenging technically, politically and socially. However, ambitious interventions to alter urban form and function will be necessary if cities are to combine high quality of life with low GHG emissions (Satterthwaite, 2008; Floater et al., 2014). Exploiting cost-effective low-carbon measures could create the enabling conditions and momentum for these kinds of long-term, transformative urban actions on climate change.

6. Conclusions

Although clearly we must be careful about extrapolating from a sample of only five cities, our findings offer useful insights into the opportunities for, and the limits of, investment in economically attractive options for low-carbon cities. Given the growing importance of cities, such opportunities have major implications for climate change mitigation; economically attractive investments in cities could lead to globally significant reductions in carbon emissions. Reinvesting the returns from such investments up to the point where all investments are cost-neutral would increase carbon savings substantially.

So could the exploitation of these economically attractive low-carbon measures in cities in the short to medium term provide a platform for more transformative change in the longer term? The answer perhaps depends on whether low carbon urban development represents what Hajer (1996) refers to as institutional learning or a technocratic project.

Under conditions of institutional learning, front-running cities would exploit the economically attractive opportunities for low-carbon development successfully, and generate both economic and environmental returns from doing so. They would also develop appropriate forms of engagement and governance to generate wider social, economic and environmental co-benefits, and through these they would increase public interest in, and enthusiasm for, low-carbon development. Institutional capacities would be built, new financing arrangements would evolve and important lessons would be learnt over time. Other cities would then be encouraged to adopt similar models, and the pioneering or front-running cities would decarbonize further. In other words, early successes would inspire other cities, while strengthening capacities that enable the front-running cities to explore more ambitious climate mitigation strategies such as structural changes in urban form.

Under conditions of technocracy, cities might implement the measures without appropriate forms of engagement and governance. The transition would become a technical exercise that runs the risk of generating social, economic and environmental co-costs and undermining social and political support and momentum for further change. Institutional capacities would be built and financing arrangements would emerge, but cities would only use these to "cherry pick" the easiest and most economic options. The front-running cities would then lose interest in further change and other cities would decide only to invest in low-carbon options where they are economically attractive. Cities would maintain their resistance to transformative changes that are likely to be more challenging, and would lock into what is at best only a marginally decarbonized future. In other words, there is a risk that cities would spend valuable time exploring options that are at best a partial response to a pressing global problem, and in the process they would crowd out the potential for deeper and more transformative change.

The policy challenge is to find ways of enabling low-carbon transitions under conditions of institutional learning. For this to happen, policy-makers and others would have to exploit the early stages of the low-carbon transition where there are economically attractive options, while ensuring that they create the conditions for the later stages of transition that could be more challenging. Low-carbon transitions would need to be seen by city-level decision-makers as an opportunity rather than a threat, and climate actions would need to be taken from the periphery of urban decision-making and mainstreamed into the key areas of urban policy such as planning, energy, housing, transport and economic development. Appropriate stakeholder engagement and governance capacities would need to be established to ensure that the transition is not a technocratic exercise but is 'socially steered' so that choices reflect different social concerns and build public support over time. New financing arrangements and delivery models need to be built, and enabling policies need to be introduced at different scales. Lessons from the front-runners then need to be identified – for example through robust evaluations of early experiences – so that good practice can be rapidly developed within and transferred between cities. And all of this needs to be done in a way that stimulates a long-term vision of, and a commitment to, more deeply decarbonized cities. If this can be achieved, then exploiting economically attractive low-carbon options in cities in the short term could be a major contribution to successful climate change mitigation at the global scale in the longer term.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2015.07.009.

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