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# Energy for cities: supply, demand, and infrastructure investment

Colin J. Axon[1] and Simon H. Roberts[2]

**Abstract** Energy is essential to all activities in all regions of a country. However the density of energy use in, and our economic dependence on, cities means that it is more critical for urban areas. Nevertheless we suggest that the provision of energy for urban areas cannot be considered separately from the national context. We will demonstrate how to assess the ability of a nation to invest in energy infrastructure for the benefit of cities. Our approach exploits datasets which are available in most industrialised countries and we select two quite different case studies to illustrate our method: the Colombia (Bogota) and UK (London). Our focus for energy sustainability in cities is quality of life and reduced fossil-fuel emissions. We will show that the main target for cities should be to improve air quality and reduce energy demand by improving energy efficiency.

## 1. Introduction

In all nations, the numbers and size of cities have grown since the onset of the industrial revolution and with it the increasing demand for energy (Ayres and Warr, 2009; Kander et al., 2013; Wrigley, 2010). Growing economies and expanding cities are symbiotic, most likely in a system boot-strapping sense. However, it is clear that the economy drives the creation, expansion and ongoing existence of cities.

Much of the national economic activity can be grouped as ‘service industry’ (Roberts et al., 2015), so we need to look at this industry along with intra-city transport. Apart from cities being where jobs are, many people choose to be in cities in order to access available services such as education, healthcare, and entertainment. There is a virtuous circle of the service industry providing jobs and thus income, which in turn is used to pay for services. There are two main constraints on this growth. The first is enterprises having to conceive new services and expand. But the most significant is the physical constraint of the time taken to build more accommodation for both the service industry and dwellings to house consumers and employees.

Until the last third of the 20th century, settlements of all sizes needed to generate power and heat by converting the fuel at the location of the final use. Even into the 1980s in the UK for instance, small (100-200 MW) electricity generating stations were still operating in built-up areas. As the demand for electricity grew, the generating capacity of each station increased. Where possible these larger plants were located close to coalfields – outside the city boundary – and not at the point of final use. Schultz et al. (2013) note that the energy demand density of cities is such that localised renewables are mismatched in their power output density to meet the demand. This means that if cities are sustainably to support highly dense populations, the power and fuels must be derived and generated outside of the city. Relying on renewables within urban areas to create zero-carbon cities is not an appropriate solution. Other driving forces for this displacement in the UK were the Clean Air Act and the rising value of land in the city. As land prices rose, many industries with high-volume, low-value manufactured products moved out of the city too. Businesses remaining in cities became part of the burgeoning service industry. Thus the patterns of energy have shifted, but remain governed by the behaviour of the economy in general.

Our analytical approach is to fuse together and mine independent national datasets which (preferably) meet international standards for collation and curation. As an interesting case study we will compare two nations meeting three criteria: 1) non-OECD and OECD, 2) Southern and Northern hemisphere, and 3) developing and developed. We chose Colombia (Bogota) and the UK (London) as comparators (Fig. 1 and Table 1). Urban economic activity as measured by services is increasing for both countries, while energy use and number of urban dwellings are increasing only for Colombia. Fuel use for urban transport by private car is decreasing for both countries, while bus use is increasing. In Bogota, local government is incentivising people to use public transport to maintain this trend. The transport of goods is vital for economic activity, but the majority of the distance traveled by LCV and HGV is likely to be outside of the city. Energy demand by transport has both direct and indirect consequences. The direct demand is for fuel, and the indirect demand is an increase in air pollution and building cooling requirements resulting from thermal pollution from vehicle engines. In addition, transport air pollution and noise discourage the opening of windows on buildings, exacerbating over heating in the hot months.

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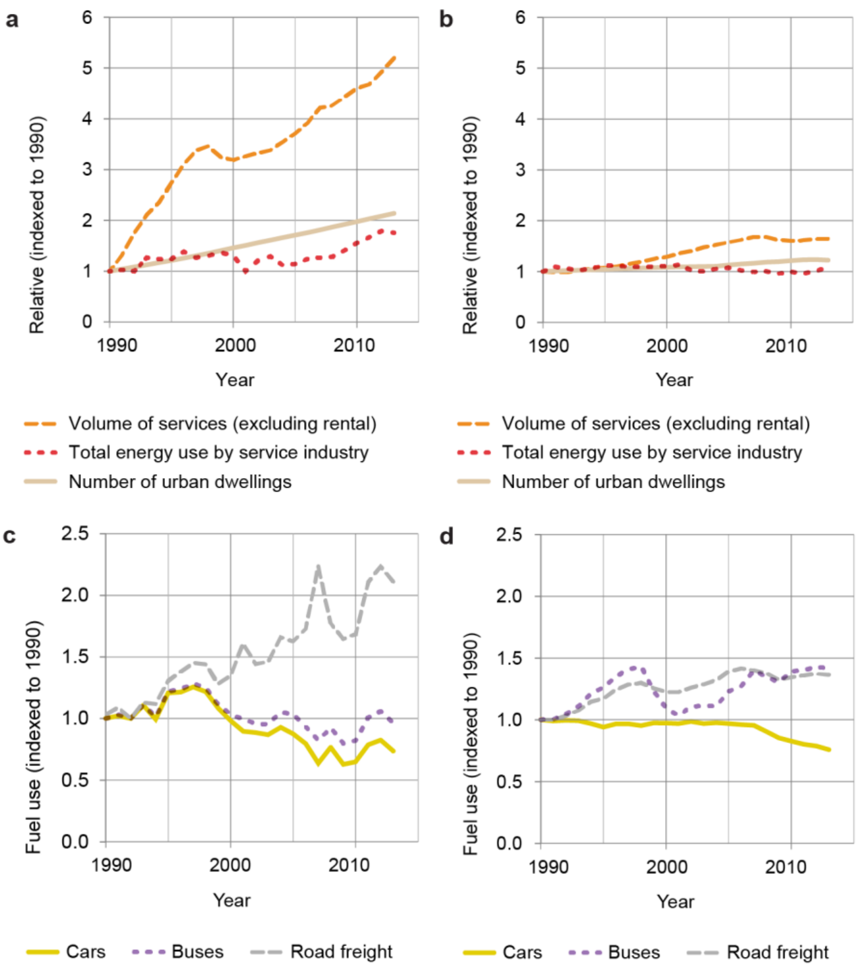

**Fig. 1. Urban indicators. Energy consumption and economic volume output of the service industry and number of urban dwellings, indexed to 1990 for (a) Colombia and (b) the UK. Fuel consumption for private passenger transport by car and bus and freight transport, indexed to 1990 for (c) Colombia and (d) the UK. Source: Banco de la República (2016), DANE (2013, 2016a), DCLG (2015a, b), DfT (2015), IEA (2015), MME (2016), ONS (2015).**

**Table 1. Selected statistics for Colombia and the UK. All data for 2012 unless otherwise stated. Source: DANE (2011, 2016a), DCLG (2012), ONS (2014).**

| Statistic | Units | Type | Colombia | UK |
|---|---|---|---|---|
| Population | million | Urban | 35.4 | 52.5 |
| | million | Total | 46.6 | 63.7 |
| Households | million | Urban | 9.9 | 21.6 |
| | million | Total | 12.7 | 26.6 |
| Dwellings | million | Urban | 9.6 | 23.0 |
| | million | Total | 12.6 | 27.8 |

An important factor affecting the ability of a city to reduce energy use is its point in development. Established cities such as London have placed value in the land across the whole area. By contrast, the sprawl of a rapidly developing city, such as Bogota, through informal settlements on the periphery offer opportunities for visionary urban planning and new buildings of high efficiency. Retrofitting of existing buildings is an inefficient, slow, and less effective though still necessary solution. In Bogota's 'formal' city, the main reason for avoiding retrofitting is the implementation of regulations that aim to densify.

We suggest that to understand the energy supply for cities, we must start with the structure of the macroeconomy. Then we must incorporate socio-technical, transport, and energy data, and finally derive the split between the urban and rural demands.

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The key data source for economic activity is the internationally agreed System of National Accounts (United Nations et al., 2009). The data are available for all countries, comprehensive, comparable, and have good time granularity over the historical period. Additional data sources are employment, national household survey, housing stock, national energy balance, and transport statistics.

As a bridge from national-level to urban, we define the rural/urban split in part depending what data are available. Dwellings is by location, households and population from the census or household survey, and transport as vehicle-km by class of road.

## 2. Energy and its changing demands

In Fig. 2 and Fig. 3 we show socio-economic and energy statistics for our case-study countries. Although our focus for this chapter is on energy, we gain insights by relating energy flows to the economy, investment, and jobs which are included in the diagrams. Thus we can assess the ability of a nation to invest in energy infrastructure, or to mitigate the effects of energy demand in cities.

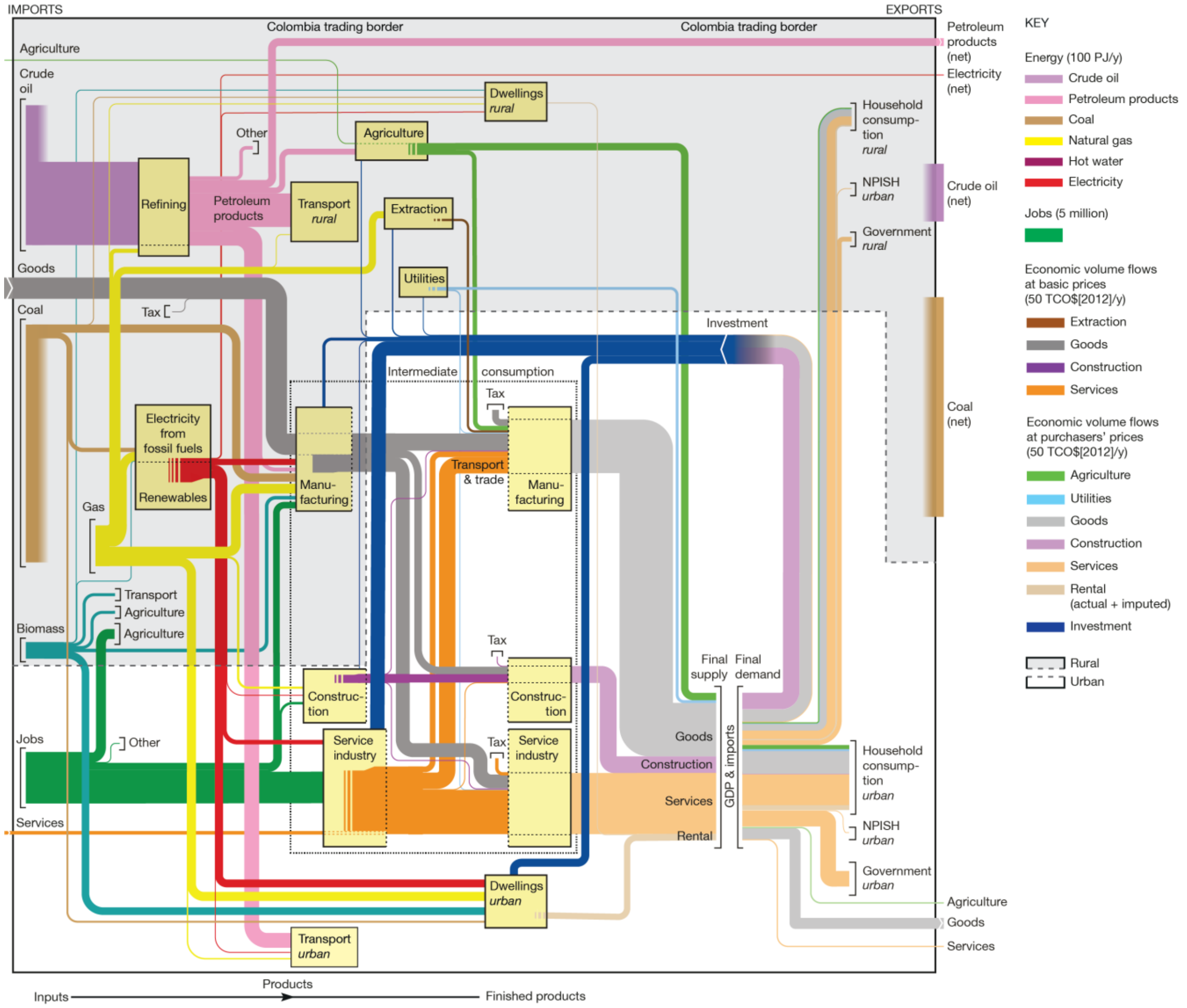

**Fig. 2. Sankey diagram of the Colombian economy using data for 2012. On the left, physical infrastructure (beige boxes) with energy, jobs and economic volume flows. On the right, component economic volume flows of final demand. [NPISH (non-profit institutions serving households), TCO$ (tera Colombian dollars]. Source: DANE (2015, 2016b), IEA (2015).**

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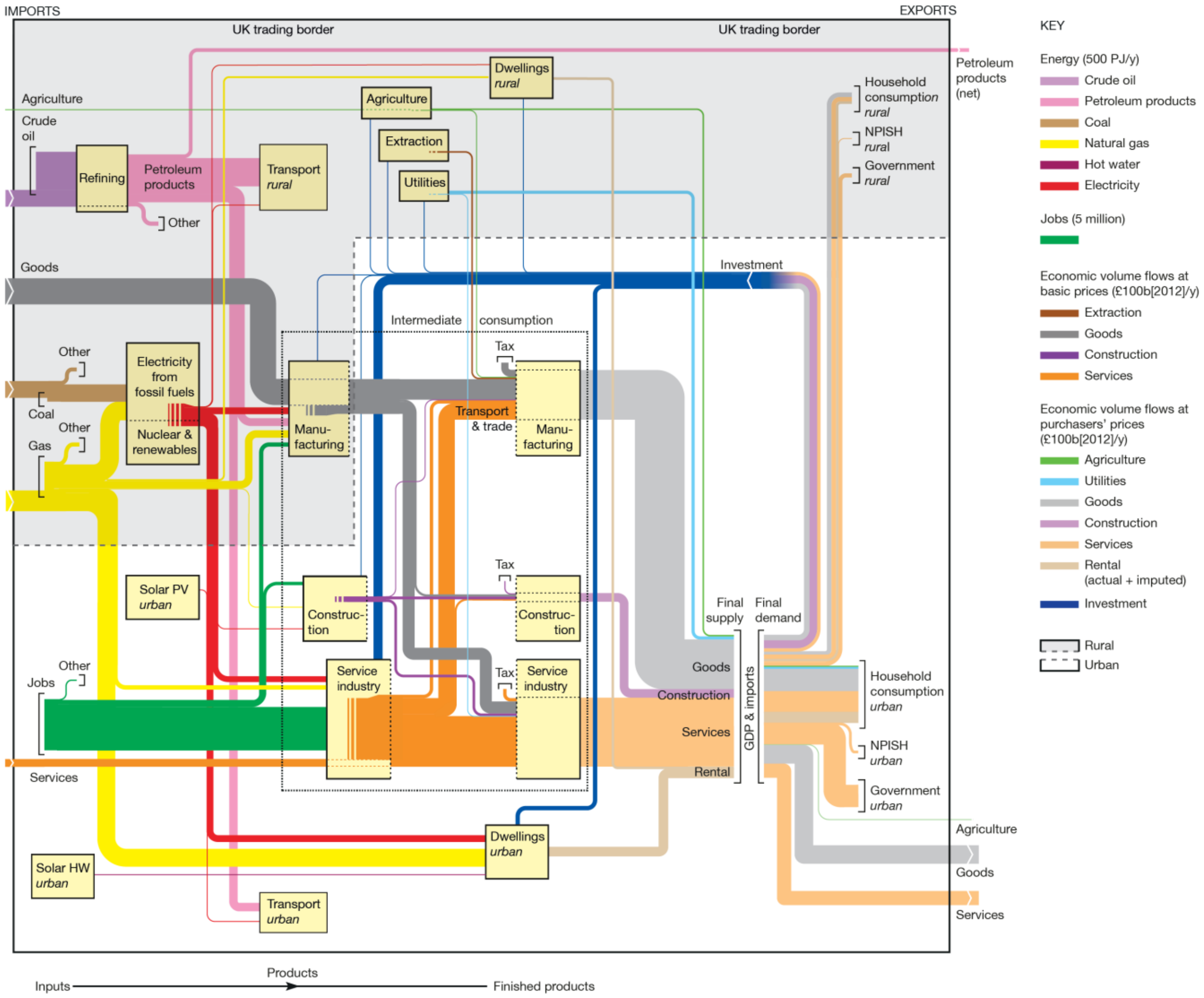

**Fig. 3. Sankey diagram of the UK economy using data for 2012. On the left, physical infrastructure (beige boxes) with energy, jobs and economic volume flows. On the right, component economic volume flows of final demand. [NPISH (non-profit institutions serving households)]. Source: Birt et al. (2015), IEA (2015), ONS (2016).**

All the boxes in the left halves of Fig. 2 and 3 represent physical infrastructure, also known as fixed capital (FC). For the FC of industry we disaggregate the economy into six groups: agriculture, extraction, utilities, manufacturing, construction and the service industry (Roberts et al, 2015). We then make a simple division shown by the dashed line between rural above this line and urban below. We assign service industry as wholly urban because it is both labour intensive and needs to be near the majority of the population. We assign construction also to urban because, as we show later, most construction takes place in urban areas. Dwellings are another type of FC, and we show these in the diagrams in both the rural and urban sections. Since we have a focus on energy we show some additional boxes for energy-specific FC. All the FC boxes in each diagram lie within an overall rectangle, which represents the trading border of the economy. Imports enter on the left and exports leave on the right.

The main purpose of these diagrams is to show and quantify using Sankey lines the various flows of energy, jobs, goods and services to and between the types of FC and final use, and then how these relate to urban areas. Each FC box has just one line emerging on the right which represents the single type of product it produces, such as goods from manufacturing. The lines on the left represent inputs needed for production, such as raw materials, so we think of these as starting on the left and flowing to the right into boxes where they are consumed. A blue line enters the top or bottom of each box to represent what is needed to increase and maintain the FC. These flows are referred to as fixed capital formation (FCF).

Economic production by industries is known as gross value added (GVA), where the output form of gross domestic product (GDP) of the economy equals the sum of GVA by all industries plus rental. Although rental of dwellings is normally categorized as a service, it is more accurate to represent it here as originating from dwellings rather than from the service industry FC. This disaggregation helps with the urban energy analysis.

One aspect of economies is how products pass between industries, referred to as intermediate consumption (IC) (Roberts et al., 2016). Only after IC are products in their final form, such as for use by households. IC is detailed in the diagrams just for the three larger industries, which is why they are shown as pairs of boxes. The addition of tax on products is shown explicitly so that the products in their final form, on the right, are at purchasers' prices.

The final destinations of products in the economy are shown in the right halves of Fig. 2 and Fig 3. All the Sankey lines for economic volume flows come together, marked 'final supply', such that their total Sankey width corresponds to the expenditure form of GDP summed with total imports. Most final consumption is by households according to whether in rural or urban. In this national accounts formalism, one component of final demand is investment, the source of FCF essential for all the FC boxes. The FCF flow has contributions from manufacturing, construction and services, but their Sankey colours are blended into blue for clarity in the diagrams.

The great value of combining energy, jobs and economic volume flows in these diagrams is the ability to reveal how energy is attributed across the economy. The purpose of an economy could be viewed as the fulfilment of final demand of household consumers (on the right). The Sankey format shows how this consumption maps back on to all forms of source energy. It explains the concepts, shows a complete picture (with no under- or double-accounting), and quantifies dependencies.

So what do the Sankey diagrams tell us about urban energy and sustainability? We note that our division between rural and urban is crude in putting all manufacturing into rural and all of service industry into urban, though more detailed data is either not available or difficult to obtain. Despite this approach to the division, we suggest it does not devalue some key observations we now make.

- Most economic activity is in the service industry (the FC box) and thus urban by our assignment. Services as the product (the Sankey line) includes the IC of retail which is a significant proportion of goods in their final form. The Sankey diagrams for Colombia and the UK are surprisingly similar within their IC dotted boxes.
- Investment, represented by the vertical blue lines, shows that most construction is of service industry and dwellings, so mostly urban, thus appropriate that we assign construction here.
- Most jobs are in the service industry with significant numbers in construction, thus mostly urban.
- Virtually all energy is sourced or generated (electricity) in the rural parts. Where there are energy sources compatible with urban area of solar photovoltaics and hot water (Fig. 3), these are very minor indeed.
- For the fossil-fuel intensity of electricity, this is low in Colombia because of the high proportion of renewables (hydropower) whereas it is a high proportion in the UK since there the contribution of nuclear and renewables is low.
- Biomass is a major source of energy in Colombia, all from rural.
- For transport, most energy use is rural but this would include passenger travel to urban areas and between urban areas, and freight transport serving urban needs.

These observations support what is well known about urban areas as a focus for jobs, economic activity, construction and a significant proportion of transport.

The demand for energy in the urban areas can be categorised by type of delivery according to the practical use of the engineered system: electricity, heat and transport. This typology fits well with the readily available socio-economic and energy data where the percentage global division between these is roughly 20/50/30. Fig. 4 shows how these energy proportions vary, either by delivery type or by use, as in the Sankey diagrams of service industry, dwellings and transport. Service industry and dwellings data incorporates electricity and heat use, whilst transport is considered separately.

Electricity is very similar between the two countries rising from 20% to 30%, while the heating proportion declines. At present it is not possible to fully determine whether this is due to fuel switching or heating reduction through efficiency (biomass to gas, or better insulation). For urban use of heat, this is mostly by urban dwellings for space heating, cooking and hot water. Heating or cooling is rare in Bogota for housing, but cooling is used in office buildings. Transport energy demand is high in Colombia peaking at 50% and only recently getting below 40%, while the UK has been stable at 20%. The Colombian urban energy demand is approximately 40% to each of dwellings and transport with the remaining 20% to the service industry, though increasing. For the UK, 50% of demand is by dwelling with 30% to the service industry and 20% to transport, all remaining stable.

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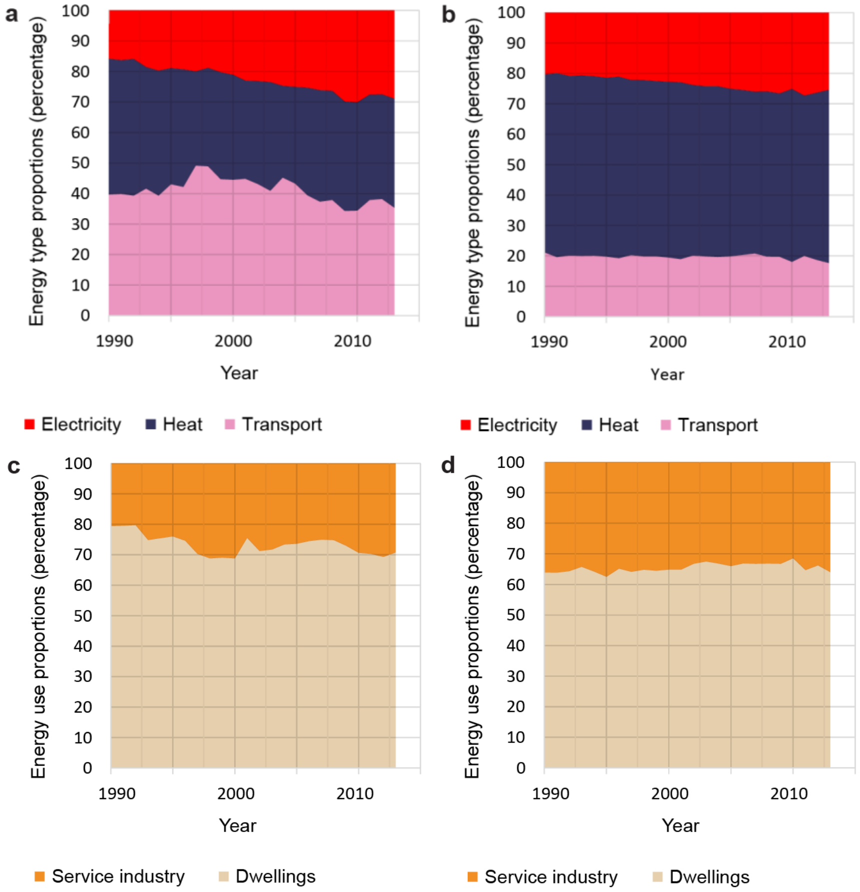

**Fig. 4. Ratio of energy types, urban: electricity, heating, transportation, for (a) Colombia, (b) the UK. Ratio of energy uses, urban: service industry, urban dwellings, for (c) Colombia, (d) the UK. Calculated using IEA (2015).**

## 3 Interpreting the urban context

We consider future changes and pressures on the urban environment by examing five issues (Table 2) arising from the three delivery types: electricity, heat, and transport.

**Table 2. Principal energy types and their issues for cities. Key: ● major issue; ○ minor issue.**

| Issue | Delivery type | | |
|---|---|---|---|
| | Electricity | Heat | Transport |
| Air quality | | ● | ● |
| Fixed infrastructure | ● | ○ | ○ |
| Thermal pollution | ○ | | ● |
| Noise | | | ● |
| $CO_2$ emissions | ○ | ● | ● |

Combustion of fuels (fossil and biomass) in built-up areas gives rise to poor air quality. The principal culprits are carbon monoxide (CO), sulphur dioxide ($SO_2$), nitrogen dioxide ($NO_2$), low-level ozone ($O_3$), black carbon, particulate matter (PM), and heavy metals. (WHO, 2016). According to the air pollution index of Buehn and Farzanegan (2013) Colombia's air quality improved by 8.6% between 1985-2005 and the UK by 6.8%.

A useful indicator of air quality is the concentration of $PM_{10}$ (particulate matter with diameter of 10 μm or less). For Bogota in 2007 the annual mean was 77 $\mu g/m^3$. For London in 2008 the annual mean was 29 $\mu g/m^3$, mostly caused by vehicles. The re-suspension of PM also affects air quality (Keuken et al., 2013). Tyre and brake wear a significant contributor (Smith et al., 2013), and will not be reduced by the introduction of electric vehicles. The 2015 level of $PM_{10}$ in

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Bogota is similar to that of London through the 1960s when the combustion of wood and coal in dwellings was prevalent. Even modest levels of biomass combustion in urban areas may lead to $PM_{10}$ concentrations exceeding that from traffic (Reis et al., 2009). Likewise, Fuller et al. (2014) suggest that increases in wood burning in London seen in recent years may undermine the reductions in $PM_{10}$ from vehicles. Smith et al. (2013) estimate that approximately 5600 UK deaths in 2005 were attributable to transport emissions.

Each delivery type requires some fixed infrastructure which constrains the rate at which each can expand. For electricity the fixed infrastructure comprises the generating stations, and transmission (high voltage) and distribution grids. For heat this would be mostly gas and its need for a pipe network. For district heating systems, an expanding city may have opportunities to install the required fixed infrastructure. Transport's fixed infrastructure would be rail, light rail, underground metro, trolley and tram, and dedicated bus roads (such as Bogota's TransMilenio Bus Rapid Transit system).

Thermal pollution results from the emission of low grade heat from sources such as air conditioning units and vehicle engines into the canyons formed by the city streets creating an urban heat island (UHI) (Mavrogianni et al., 2011). It gives rise to heat stress in work, moving around outside and sleeping, particularly affecting the infirm and elderly. The use of air-conditioning in small offices, refrigeration in retail, and mechanical air-handling with large-scale HVAC equipment are growing sources of thermal pollution. Countermeasures to these maladaptation feedbacks then further increase energy demand. Other contributory factors of thermal pollution are the thermal capacity and conductivity of all the elements that make up the city (not just buildings and roads), solar absorptivity, weather conditions, and levels (and type) of vegetation (Kolokotroni and Giridharan, 2008).

Noise from transport, and to a much lesser extent from the motors and fans of air-conditioning units, affects energy use by restricting when windows can be opened. This increases the level of cooling demand met by air conditioning.

The amount of attributable $CO_2$ emissions results from the type of energy used and the total demand. For the heating of buildings, a useful measure of the way cold weather conditions affects energy demand is heating degree days (HDD)[3]. Bogota at latitude 5 °N and altitude 2640 m had about 800 HDD in 2015, while London at latitude 51°N and altitude 5 m had about 1500 HDD. The UK had notably cold winters in 1996 and 2010, which also shows up as spikes in Fig. 7(a) (in Section 4). This difference in HDD partly accounts for the much lower heating requirements in Table 3 of Colombia. Currently in the UK the UHI is viewed as a positive effect in winter.

While the use of electricity has no issues of air quality and minimal from noise, its issues are overall demand, thermal pollution and $CO_2$ emissions. It is helpful to use three groups for the uses of electrical power. The first is lighting, low and medium power devices, all of which can most effectively be supplied by electricity. The second is cooling (air conditioning). The third is some requirement for space and water heating. The rate of change in demand for these three groups will be different. So what is driving the increase in electricity demand when many electrical devices such as lighting are becoming more efficient? The number of types of device, and the growing use of information and communications technologies all contribute. But the electrification of heating of water and space is a bigger factor, as is the requirement for cooling.

Electricity demand for the service industry is partly for air conditioning, and cooling degree days (CDD)[4] are one factor in quantifying the activation of air conditioning. The CDD for Bogota was zero in 2015, and 27 CDD for London, but these might increase if climate change leads to more severe summer heat waves and their associated health impacts (Kovats and Hajat, 2008). A better indicator of cooling needs is 'weighted cooling degree hours', which is more closely related to the likelihood of thermal discomfort than CDD (CIBSE, 2014). Air temperature alone is a poor indicator of the human thermal environment, Jendritzky and Kalkstein (2015) describe more suitable indicies.

Overall demand for the three types of energy can be drawn together by looking at the contribution to $CO_2$ emissions that can be directly attributed to all urban activities. We show application of the Sankey format for mapping $CO_2$ emissions to industries, dwellings and transport in Fig. 5 (7sD) (Colombia) and Fig. 6 (7sC) (UK). They show urban proportions of total national emissions as 20% for Colombia and 50% for the UK., Thus the urban per capita emissions of 0.49 $tCO_2/y$ for Colombia and 4.7 $tCO_2/y$ for the UK.

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[3] HDD: for each day, the number of degrees that the outside temperature is below a nominal threshold requirement for indoor heating. The reference value for the UK is 15.5 $^oC$. Data can be calculated using http://www.degreedays.net/

[4] CDD: for each day, the number of degrees that the outside temperature is above a nominal threshold requirement for indoor cooling. Most countries reference to 22 $^oC$.

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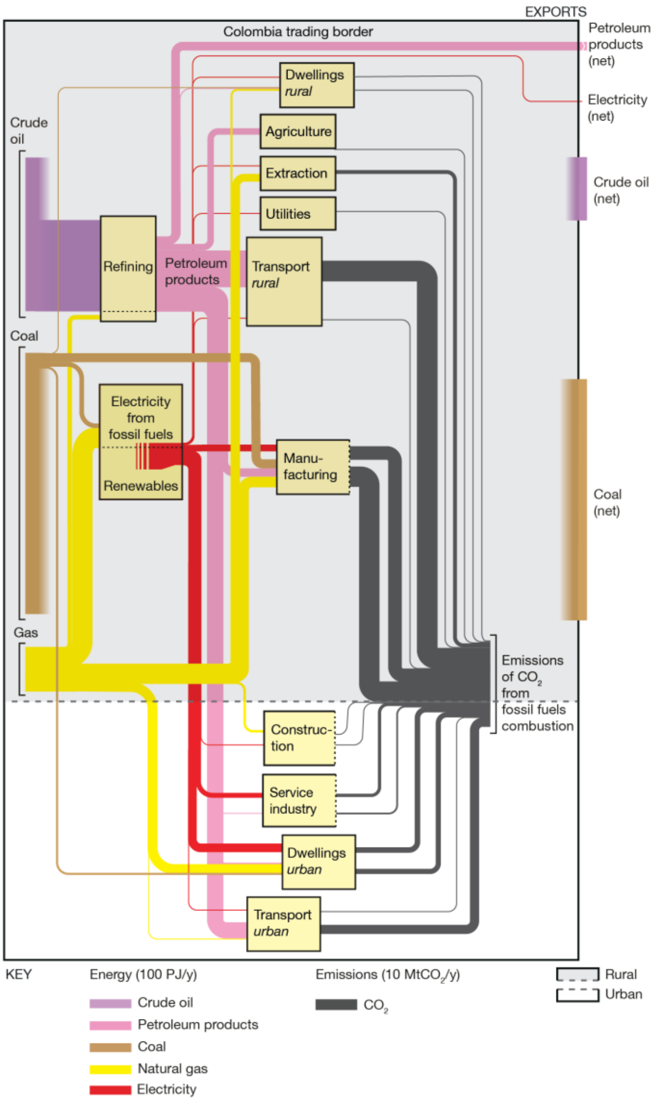

**Fig. 5. Sankey diagram for Colombia of $CO_2$ emissions in 2012 resulting from combustion of fossil fuels. Biomass is not included since the complete biomass cycle means there is no net contribution of emissions to the atmosphere. Source: IEA (2015).**

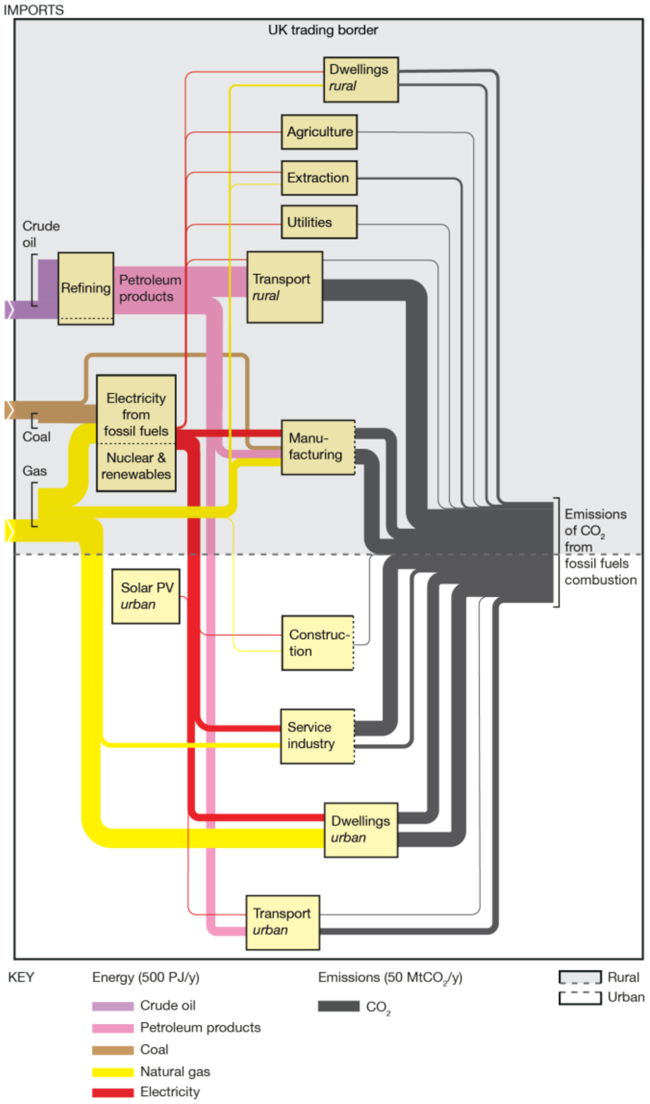

**Fig. 6. Sankey diagram for the UK of $CO_2$ emissions in 2012 resulting from combustion of fossil fuels. Source: IEA (2015).**

## 4. Reducing the demand for energy and its impacts

Sustainability of energy in cities is about addressing the issues in Table 2. The principal solution to these is to reduce the demand for energy, followed by substitution of energy type. We can see from the relationships between energy types and their uses (Fig. 7) that progress has been made in both Colombia and the UK. There are downward trends in both Colombia and the UK for the heat intensities per service industry job and per dwelling. However, the electricity intensities have little changed since 1990. The essential features are summarised in Table 3, with relevant statistics for transport in Table 1. In Fig. 7 the huge reduction in heat intensity for dwellings throughout the 1990s for Colombia was due to replacing the use of solid fuel with gas as part of a programme of providing energy services to the poorest households (Barrera-Hernandez, 2004; Grubler et al., 2012).

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**Table 3. Summary of the energy intensities for 2013. Source: DCLG (2012), IEA (2015), ONS (2016).**

| | | | **Colombia** | **UK** |
|---|---|---|---|---|
| Heating | Service industry | GJ/y per job | 2 | 16 |
| | Dwellings | GJ/y per dwelling | 11 | 47 |
| Electricity | Service industry | GJ/y per job | 3 | 13 |
| | Dwellings | GJ/y per dwelling | 6 | 15 |

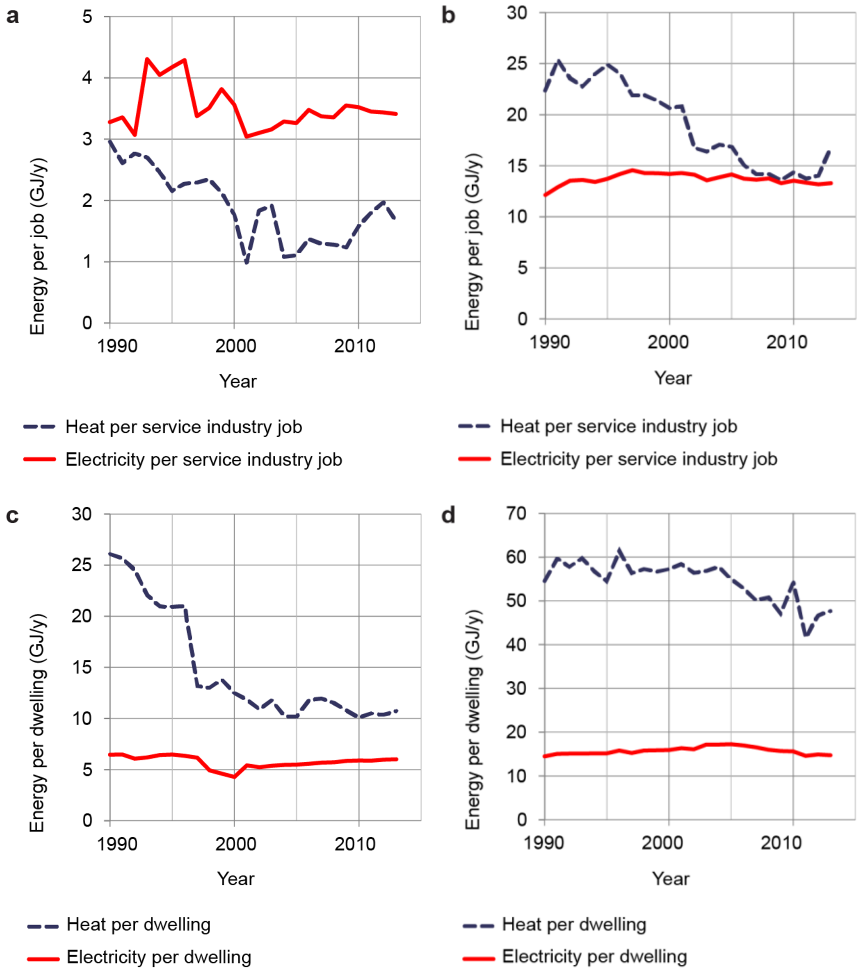

**Fig. 7. Energy intensity by jobs in services, (a) Colombia, (b) the UK. Energy intensity by each dwelling (not able to distinguish between rural or urban), (c) Colombia, (d) the UK. Source: DCLG (2012), IEA (2015), ONS (2016).**

### 4.1 Dealing with the Effect of Location on Demand

The geographical context for a city has an impact on its options for energy efficiency and reducing energy demand. A city's latitude and climate determine its potential for solar generation and the the needs of occupants' thermal comfort. Furthermore, a city's point in development affects the available options. A city with an established set of infrastructures is difficult and expensive to change, while new and growing cities have better opportunities in the master planning of the layout. For both established and new cities standards, and regulations of building efficiency need to be expanded in scope and enforced (IEA and United Nations, 2013).

The proximity to energy sources by pipe, wire, road, rail and water are a key determinant of the range of actions which are possible. Having identified the need to site the main electricity generation outside of the urban environment, we note that transporting low grade thermal energy more than a few hundred metres is impractical. The production of hot water using solar gain is only feasible at the point-of-use. Good conditions for solar hot water, along with photovoltaics, are latitudes within about 50 degrees of the equator as long as the conditions can avoid sand which would other-

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wise severely reduce solar efficiency. But even in the right climatic conditions, Webb (2016) shows that city-scale governance can be a barrier if at odds with the national regulatory framework.

The key features of climate that affect energy demand for thermal comfort are:

- Whether the winters can be very cold winter or just mild.
- Whether the summers are very hot summer and humid.
- Whether there prevailing winds that could be harnessed for cooling.

A high number of HDDs means that building regulations should focus on insulation of walls and windows and reduction of uncontrolled drafts so that ventilation is optimal to avoid moisture build up and condensation. Shielding of buildings from high winter winds also helps to reduce heat losses. If solar conditions are sufficient in winter, then glazing should be optimized towards the equator for solar gain. For new-build housing, optimal solar orientation can reduce both heating and cooling loads at minimal cost (Hemsath, 2016).

By contrast, for a city with a high number of CDDs, an obvious step is to minimise the glazing to wall area ratio, and maximise solar shading of any glazing from the sun to avoid compounding high air temperatures. Kolokotroni et al. (2012) suggest that if internal heat gains are reduced night cooling using natural ventilation will have a beneficial effect on energy performance. If there is prevailing wind then buildings should have windows that open for this natural ventilation while still maintaining security and minimizing incursion of noise. Where there is little wind, tall buildings can exploit the stack effect of thermal buoyancy to drive their own natural ventilation. If night time temperatures are low then buildings can be designed with internal thermal mass which is pre-cooled by night time ventilation so as to moderate temperature rise during the day. Increasing vegetation, parks, green roofs, and green walls will add shading and increase evaporative cooling (Kolokotroni and Giridharan, 2008). At the same time, increasing the albedo of surfaces, cool roofs and pavements are useful additional measures (Hirano and Fujita, 2012). These will help to reduce the heat island effect and thus reduce the energy demand for cooling.

Mitigating heat waves should not simply mean increasing the use of air conditioning. In hot conditions the distribution cable capacity is reduced, jepardising electrical stability (Choobineh et al., 2016) and increasing the likelihood of power failures, at the time of additional electricity demand (Salagnac, 2007). Hicks and Menne (2015) given several examples of national and regional heat wave plans for public health interventions. Recommended actions include health education, contacting high-risk individuals, and the opening of cooling centres (Kovats and Hajat, 2008).

Transport remains in both countries mostly a single fuel user, i.e. petroleum products. As the rate of car ownership in Colombia is lower than the UK, it is reasonable to expect that as the Colombian economy grows, so too will the total number of cars in the country and their use. It is likely too that the cheapest fuel source will be used, thus the provision of energy for transport will remain dominated by petroleum products for the near and medium term. The infrastructure for the internal combustion engine is entrenched in terms of both economics and skills. Improving vehicle efficiency and traffic management are of central importance to reducing energy demand (Erickson and Tempest, 2014). Some potentially helpful actions are to remove the heavy metal and $SO_2$ at source, so promote the use of lead-free and low-sulphur fuels. Remaining tailpipe emissions such as carbon monoxide, VOCs and $NO_2$ can be reduced by the mandatory fitting of catalytic converters. Reducing VOCs and $NO_2$ will lower the rate of formation of ground-level ozone. Diesel particulate filters will reduce PM.

A transition away from petrol and diesel may be facilitated by bioliquids, LPG, natural gas, and perhaps hydrogen. But the replacement of the internal combustion engine by the electric motor is dominated by the need for investment in a different infrastructure. Although suggested by many, there is no serious prospect of EVs participating in the electricity grid as short-term energy storage to offset the operating and ownership costs (Bishop et al., 2016). Furthermore, there is uncertainty whether the overall lifecycle assessment for electric vehicles is better than of the internal combustion engine (Hawkins et al., 2012). With a mostly low carbon electricity generation portfolio Hawkins et al. (2013) suggest that $CO_2$ and GWP may be better than using gasoline, but still indistinguishable from using diesel. Hawkins et al. (2013) also suggest that environmental impacts of electric vehicle battery and powertrain manufacturing may be greater than for the internal combustion engine. Within the city, however, the potential for zero tailpipe emissions confers significant benefits for air quality with a positive knock-on effect for building energy use.

There is a clear-cut need for demand reduction of electricity and heating for a city such as London with all buildings benefitting from reliable power supply. Although some London households are in fuel poverty, making the housing stock more energy efficient and reducing the need for travel improves their state and the overall state of the city (Erickson and Tempest, 2014). Bogota households and businesses would also benefit from energy efficiency measures. However, without city-wide resilient energy infrastructure, the need for new supply remains an important requirement. This brings us back to the socio-economic energy modelling of the macroeconomy in section 2 – what, how much, and how fast can a national economy support (and maintain) growing cities? Investment represented by the vertical blue lines in Fig. 2 and Fig. 3 show there is much construction of service industry and dwellings with opportunities to implement new energy priorities.

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## 5. Conclusions

We have shown that by bringing together national datasets on energy, population, transport, and the economy we can gain insight to energy use in the city context. Nations need to be aware of indicators that demonstrate non-sustainable trends. The data fusion method we have used is one way to visualise the links between economic activity, energy and power demand, and the consequences on society (including $CO_2$ emissions). Chasing the unattainable dream of zero-carbon cities may lead to distorted national priorities and policy objectives. The potential for urban areas to generate their own energy is very low. If the climate is right for solar input, then urban areas can make a contribution. Big energy facilities – along with agriculture and manufacturing – are best-suited to rural areas.

However, that does not absolve cities and their authorities from 'getting their own houses in order' by reducing energy demand for electricity, heat, and transport. How a city goes about this is location and climate dependent, but the key priorities for sustainability should be improving air quality and reducing energy demand directly by a radical step-up in energy efficiency. But improving the energy efficiency of buildings and reducing the emissions from vehicles needs more stringent regulation which is then enforced.

Mitigating the UHI is a virtuous feedback system. If the air quality is improved, then natural ventilation becomes a realistic prospect. A logical first step is to reduce the use of the internal combustion engine within the city. This also reduces thermal pollution from the engines and exhaust gases. Then anthropogenic heat emitted from buildings can reduce. Pursuing these objectives simultaneously addresses fuel poverty, indoor comfort, health, infrastructure resilience, and several types of pollution. Particular attention is needed to address heat stress with minimal increases in the use of air conditioning.

### 5.1 But is it affordable?

Most new economic activity is associated with the urban environment and the Sankey diagrams show where the currently available investment is being made – to increase investment means graphically to widen the blue line. This investment comes from consumption, and increasing total investment (for all activities) by 10% translates as a reduction in household consumption of approximately 3%. Although this relatively small price has significant leverage the rate of change is slow at present. One of the main observations is that the service industry is absorbing the largest share of the available investment, but these jobs already have a lower energy intensity. The difficulty of switching where the investment is made is compounded because the service sector has a lower energy intensity per job, thus it is cheaper and easier to create jobs in this sector.

One way or another, the economy always pays for investment, but does high capital expenditure pay-off? The approach should be to assess how aggressive a deployment rate is possible, work out how much investment this requires, then examine the effect on the macroeconomy.

What can Bogota and London do? Are they all that far from an economic trajectory that will allow investment in energy efficiency and infrastructure, or is air quality too poor? Before climate change bites, will the Colombian economy become robust enough to make changes (in Bogota)? Will the UK choose the path of reducing energy demand? If not, then both may go straight for air conditioning as it will be the cheaper than improving air quality or the quality of the buildings in which we live and work.

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