Chapter 6
Big Data for Urban Energy Reductions

6.1 Introduction

Globally, primary energy consumption has shown an extraordinary rise since 1900. In that year, energy use was only about 44 EJ, much of it fuel wood, but it rose to 101 EJ by 1950, and then to 574 EJ by 2014 [14, 22]. Because of the urgent necessity to seriously tackle climate change, the possibility of rising fossil fuel costs associated with depletion of easily-produced reserves, and uncertainties over both the technical potential of energy alternatives and their long lead times for implementation, global future energy use will most likely need to be curtailed [23, 25, 29]. Consequently, per capita energy use in many cities will have to fall, particularly in the high-energy consumption cities of the OECD [24]. A visual reminder of the high energy consumption of cities can be gained from satellite images of the Earth at night, with brightly lit city regions clearly visible.

Although big data could be an important aid to other areas of urban sustainability, as we discuss in other chapters, it will simply be *essential* for sustainable energy production [18], smart grids and energy efficiency [32]. In Chap. 1 we reviewed the possible approaches for a sustainable energy system in the future, concluding that RE will need to supply the greater part of our future energy needs. We also pointed out that only intermittent energy sources, largely wind and solar energy, have sufficient global technical potential to allow for the needed large expansion in global RE production. Yet the shift to non-fossil sources of energy is occurring much too slowly. When the first IPCC report was released in 1991, non-fossil fuel electricity accounted for 36.7% of global electricity generation, but by 2014, this figure had fallen to 33.2% [5]. Although global solar energy production is still growing exponentially, wind energy production growth is now growing only linearly.

Germany, a leading country in solar energy, has around 1.5 million photovoltaic (PV) cell installations, largely small-scale domestic roof-top installations, which together with medium and large scale solar PV farms, in 2014 generated as much as 7% of German electricity production [43]. The traditional electricity supply model

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involved a few large generating plants, with each typically having a capacity of 100 MW or more, supplying perhaps millions of households as well as many industrial and commercial customers. In contrast, with the rapid global expansion of rooftop PV units, electricity utilities are having to cope with millions of both producers and consumers. A further major difference is that, traditionally, utilities could plan their production, with baseload plants run continuously, and extra units brought in to match varying daily and seasonal demand. With intermittent solar and wind energy, production not only cannot be planned, but electricity output from these sources can be reliably estimated only a limited time into the future.

However, intermittent renewable electricity will be more costly than fossil fuel electricity, particularly if large amounts of storage prove necessary [25]. Storing wind or solar electricity will first require conversion of the excess electricity to another energy form such as chemical energy (as in batteries), hydrogen, methanol, or compressed air stored in underground caverns. It must then be re-converted back into electric power as needed, with further energy losses and costs. To encourage a major shift to these costlier non-carbon energy sources, a carbon tax (or some other means of pricing carbon) will therefore prove necessary. According to the IPCC [13], global temperatures increases (relative to pre-industrial temperatures) need to be kept below 1.5–2.0 °C if we are to avoid serious anthropogenic climate change. The modelled results of van Vuuren et al. [38] showed that to keep within this limit, a global carbon price as high as US$ 700–900 per tonne of carbon (or 200–250 US$ per tonne CO_2) would be needed by 2050, and would then need to be permanently maintained at this level.

Chapter 1 stressed both the need for more RE production, especially intermittent energy and the need to reduce overall energy consumption as fossil fuel use is progressively cut back. Although this chapter will concentrate on electricity, other energy carriers will also be important for urban areas in future, even if they are mainly ultimately sourced from renewable electricity.

The rest of this chapter consists of three parts. Section 6.2 discusses electricity production and the need for smart electricity grids in an era of multi-source intermittent energy producers. Sections 6.3–6.6 look at the demand side: how can big data help reduce energy use, from individual buildings through to the city as a whole? This brings us to an important general point: for many areas of urban sustainability, including energy conservation, big data is only an *enabling technology*. Other changes will need to occur for big data to realise its potential. A final section (Sect. 6.7) stresses the importance of an integrated view of urban energy consumption, necessary for reducing energy use and its consequent emissions.

6.2 Smart Grids: A Necessary Part of Sustainable Energy

In general, the purpose of smart grids is to enable ‘a two-way flow of power and data between suppliers and consumers in order to facilitate the power flow optimization in terms of economic efficiency, reliability and sustainability’ [10]. As with the terms ‘big data’ and ‘smart cities’, the phrase ‘smart grids’ means different things to different people. In some cases it is simply a wish list of the desirable properties any grid should have. Zora Kovacic and Mario Giampietro [15] have provided a list derived from the published literature of their—sometimes potentially contradictory—properties:

- Instantaneous matching of electricity supply with demand
- Reducing peak demand
- Enabling the transition to RE electricity
- Securing energy supply
- Reducing blackout frequency
- Increasing overall energy efficiency
- Guaranteeing electricity access for everyone
- Decentralising electricity generation.

Blumsack and Fernandez [4] summed up the vital importance of big data and its application to the smart grid as ‘the ability to process and analyze large amounts of information.’ But as they also pointed out, moving to smart grids will add to the complexity of the already complex conventional electric grids. They thus warned that there was no guarantee that blackouts would be less common or less severe with smart grids. As an illustration of this increased complexity, Andreottola et al. [1] have discussed how the introduction of large numbers of customers as small energy generators into the grid—as in Germany—brings with it a number of technical problems in addition to the random availability of intermittent RE.

In Sect. 1.2, we argued that attempts to ‘green’ fossil fuel-based grids by using CCS and/or geoengineering are unlikely to succeed, even assuming an adequate future supply of accessible fossil fuels. Several proposals have also been made for enabling the conventional approach of a few large generating units supplying many consumers to continue in an RE future, rather than decentralising generation as in the list above. An ambitious approach proposed by the Desertec project foresaw solar (and wind) energy produced from energy farms in the deserts of North Africa and the Middle–East sent thousands of km to supply electricity to European grids [25].

Even more visionary schemes have seen solar production from energy farms in all the worlds deserts, in both hemispheres, and in various time zones, connected in a worldwide grid to even out daily and seasonal supply fluctuations. Another method for ensuring a non-intermittent supply of solar electricity, originally proposed more than four decades ago, is to produce solar energy from an array of suitably positioned satellites made with large light-weight structures covered with PV cells, convert it to microwave energy, transmit this power to Earth-based receiving stations, then finally convert it back to electricity [20]. All these ambitious schemes would be extremely expensive, would take decades to become operational, and would raise many political and environmental problems and risks. For example, would countries be prepared to risk placing their electricity supply entirely in the hands of a distant country? At present, in marked contrast to oil, very little of the world’s electricity production crosses national borders [5, 14].

Decentralising electricity generation, one of the properties of smart grids listed by Kovacic and Giampietro, would overcome at least some of these problems. One of the advantages of decentralisation is a reduction in the need for new transmission line capacity. In many mature industrial countries of the OECD, adding new capacity has proved very difficult, because of land constraints for new right-of-way and citizen opposition [3]. What is more, with the planned increase in RE electricity, transmission capacity will need to rise disproportionately, because it will have to be designed for peak production of intermittent electricity, not the average [26]. Local generation can help get around the problem of limits on transmission line capacity. So, of course, can reductions in electricity demand, discussed below.

Apart from demand management, discussed in Sect. 6.3, another obvious approach to dealing with the transition of electricity grids to intermittent RE is to provide energy storage. California has mandated that 1.32 GW of storage capacity be installed in the state by the year 2020 [16]. This energy storage can be at a large scale and provided by the grid utilities, as with the already common pumped water storage (in use since 1929 [41]), or the much rarer compressed air in underground caverns. If batteries are used, however, one possibility for these highly modular devices is for at least some of the capacity to be sited at domestic houses and other buildings; just as with PV rooftop cells for electricity production, some energy storage capacity would also be sited domestically.

Wang and colleagues [41] have discussed how such a system might work. Domestic energy bills have two important components: the wholesale cost of electricity and the investment costs for the distribution network. The latter cost can be reduced by the use of low voltage distribution networks. They developed a model to minimise the sum of both costs, in which domestic storage devices (in this case lithium ion batteries) are jointly operated by the household and the utility. They found that compared with the base case in which households operated the batteries solely to minimise their own power costs, joint operation, although it increased complexity, enables overall system costs to be reduced, which in turn would cut electricity costs for the household.

6.3 Urban Domestic Energy Consumption

Domestic energy use is typically around 20% of total primary energy use in OECD countries, with a similar percentage used in the commercial sector. In the US, about two-thirds of this domestic use is for space heating and cooling, and water heating [27]. Like urban transport, domestic electricity, gas and water bills often have high fixed costs, which discourage households from cutting energy or water use. Sometimes electricity can even be at zero cost to householders: Mikael Elinder and his colleagues [11] have discussed the case of a large apartment block in Sweden, where the residents were allowed unlimited electricity usage as part of their rent. As expected, when market-based charges were introduced for 800 of the apartments as an experiment, electricity use for these apartments dropped markedly compared with the remaining 1000 apartments still getting free electricity. As with urban transport, for reductions to occur, the structure of costs will need to change, with variable costs increased and fixed costs lowered.

Even worse, there are often *perverse incentives*, in that unit costs for energy are often lower for greater consumption. The fixed costs could be decreased anyhow in future, because the smart meters already adopted by grids in a number of countries can be read automatically, saving meter reading costs. Smart meters can supply information (such as real-time electricity prices) to both householders and electricity supply officials on both power use by individual electrical devices and the timing of power consumption. They can also determine what appliance is drawing power, as each has a different power consumption 'signature'. In contrast, 'time of use' meters can only differentiate between peak and off-peak usage [4].

Perhaps partly because of the present adverse cost structure, the installation of smart meters by itself has so far had a negligible measured impact on domestic electricity consumption [40]: a Swiss study found that potential electricity savings from smart meters were only 5–6% [46]. In the Swedish study discussed above, installing apartment level billing was found to reduce electricity use by about 25% compared with the apartments where no meters were installed [11]. Electricity prices for domestic consumers also vary greatly even for OECD countries, ranging in 2015 from under 10 US cents to over 30 cents per kWh, and industry prices for electricity (and natural gas) are often less than half that for domestic consumers [14].

More generally, researchers have found that merely providing more information to the public on energy consumption, or why energy savings are needed, has not been very successful [9, 35]. As UK energy researcher Steve Sorrell [37] has put it: 'With energy costs being small, largely invisible and poorly understood in most relevant situations, the more common situation is unreflective, habitual energy consumption in which energy costs are secondary to other factors such as convenience and symbolism and where energy-using behaviours exhibit considerable inertia.' Supporting policies are needed to supplement more detailed information.

The results of interviews with UK householders also argue against viewing the domestic energy conservation problem as a simple information gap [35]. Not only does the information provided need to fit in with the householder's personal circumstances, but it has to be understood by the householder. Although relating energy savings to lower energy bills is one way of doing this, this self-interested approach runs the risk of crowding out deeper changes, and in any case is self-defeating if changes in energy prices render the money savings trivial or, worse, negative—the same is true for petrol savings in private transport [28], where real costs have fluctuated greatly in recent decades.

Nevertheless, some researchers feel confident that better application of various social psychological principles can leverage the energy information provided into much more significant energy savings. Various approaches that have been tried to promote such pro-environmental behaviour (PEB) include: goal setting, where an energy reduction target is set; comparison of individual consumption with others; and improving the timing and targeting of the information [46]. Tom Hargreaves and others [12] found that although householders' knowledge about details of their electricity use increased with increased information provision, reductions in use beyond a modest level proved difficult to achieve. The authors suggested that the lack of official support for electricity reductions was largely responsible.

But what all these accounts miss are the profound changes that the combination of smart grids and the dominance of intermittent RE for electricity supply will bring in the future. Today (as we saw for Germany), and even more so in the future, many householders, and owners of non-residential buildings are—or will be—both consumers of electricity *and* producers (mainly through roof top PV cell arrays) [4]; they can be regarded as *prosumers*. As active producers, they will have far more interest in energy production and consumption than is presently the case, particularly in the unit prices for electricity they are generating.

In Sect. 6.2, the ‘instantaneous matching of electricity supply with demand’ was listed as a (desirable) property of smart grids. We can only guess as to how this could be achieved in an intermittent energy future, but load management using big data could be the cheapest approach. One possibility is that domestic electricity consumers will receive daily renewable energy generation forecasts, just as today they receive weather forecasts for up to a week ahead. (In fact, the two types of forecast are closely related, given the dependence of RE on wind, insolation levels and cloud cover). These forecasts may be accompanied by forecasts of the unit costs of such electricity. Households could then save on electricity costs—which are likely to be much higher in real terms than today’s—by shifting some activities to times predicted to have low unit electricity costs because of plentiful wind and/or insolation. Possible activities would include clothes washing (and clothes drying, where, as in the past, wind energy could be used directly by use of clothes lines), household vacuuming, recharging any domestic storage or electric vehicle batteries, and so on. Just as today we consult official weather forecasts in order to decide whether to take a raincoat and umbrella, in future we will attend to energy supply and cost forecasting to decide upon the timing of activities. Householders will come to accept the resulting unit price variability in the same way as weather variability is accepted, and will realise that electricity on demand at any time—at least at affordable prices—is a relic of the fossil fuel age, and is no longer a feasible option in an era of intermittent RE.

Eventually, households will come to know the seasonal variations in energy supply for their region and thus how energy costs vary over time, and will use this knowledge to guide their (new) daily routines. (In some cases seasonal energy supply and demand will be a good match: in warm regions air-conditioning will be in greatest demand precisely when insolation, and thus supply from solar energy, is also at its peak.) It may be as simple as less electric power being available in winter if RE is mainly produced from solar energy and none at all after sunset. For solar thermal electric systems, some storage of power as thermal energy is possible after sunset, so unit price changes should be more gradual. In contrast to today, night time electricity prices could well be higher than daytime prices. If hydro is important, it will depend on the annual rainfall variation in the catchment area. For wind power, there may well be daily as well as seasonal variations.

We have to consider not only households but also larger electricity consumers, such as commercial buildings and industries. Some industrial processes, such as aluminium smelting, cannot tolerate any interruption to their power supplies and will have to pay a premium for this uninterruptible service. But commercial offices and some industrial operations will be in a similar position to households, and can time shift at least some of their energy use.

How relevant is the above discussion to the cities low- and middle-income countries? For a start, grid connection rates are usually very high in middle-income countries. It is 100% in China and already nearly 80% in India, and approaching 100% in most Latin American countries. Although connection rates are usually much lower in tropical African countries—sometimes less than 10%, connection rates in cities are far higher [45]. Given that these countries are usually well-situated for PV energy, smart grids should be just as relevant as in OECD cities.

6.4 Smart Grids and Electric Vehicle Charging

Many commentators see battery electric vehicles (EVs) as the future for transport, as a means of both reducing urban pollution (both air and noise) and transport oil dependency. Further, if the electricity was supplied by RE, transport GHGs would also be greatly reduced. Although by mid-2016, over 11 million hybrid EVs and over 1.5 million plug-in EVs had been sold worldwide [44], their introduction over the past two decades has been slow, given that the total global car fleet in 2014 numbered over 1000 million [33]. In follows that their impact on electric grids has so far been minimal, particularly since hybrid EVs run on conventional, mainly oil-based fuels, but with an electric drive train. Although China has tens of millions of electric bicycles, their grid impact is again negligible.

All this could change in the future if full battery EVs were to replace conventionally-fuelled cars, buses, and even some freight vehicles on roads. One estimate is that the global car fleet will rise to 2167 million by 2040, mainly by the continuation of the rapid growth in the presently low-car ownership non-OECD countries [33]. Even with existing car ownership levels, household domestic electricity use in typical OECD cities would be roughly doubled by the charging needs of these vehicles [34]. Further, charging would usually be done during the evening peak period for domestic energy use, which could overload existing grids. Electric grids would then face two problems: integrating intermittent RE as the dominant electricity source and managing the power load from EV charging. Smarter grids would be essential for resolving these problems.

One strategy discussed for overcoming these problems is to connect EVs to the grid so that their batteries could be used for ‘vehicle-to-grid’ (V2G) energy storage. The vehicle owners, whether private owners or fleet operators, could then sell electricity to the grid when the demand for electric power exceeded the available supply. Today, private vehicles are parked for about 95% of a 24 h day [31]. Their connection to the grid during this idle time would enable transfer of electrical energy to and from the vehicle's battery pack. In addition, V2G technology could help regulate voltage and frequency, and provide spinning reserve.

Nevertheless, we think that global EV numbers will never rise to anywhere near even existing levels of vehicles. Their power demands would simply be too high in a world which will need to significantly cut global energy consumption, if fossil fuels, the present energy mainstay, have to be phased out. Further, electric public transport can (and already does in many cities) also deliver urban air pollution benefits and GHG reduction benefits, given that it is several times as energy efficient as private travel. But with the high cost of pure EVs compared with conventional vehicles—largely because of the cost of their battery packs—car sharing could become common, with the vehicles owned by 'Mobility Service Providers' [34]. Public transport and taxis can be considered to already operate in this mode. Shared vehicles would be driven many more annual km than today's vehicles (just as today's taxis and public transport vehicles are), and consequently would be parked less often, especially during daytime hours. (Fully automated vehicles could also encourage car-sharing, but as explained in Chap. 5, we consider their widespread introduction unlikely.) With night-time battery recharging, vehicles would be drawing grid power at a time when no solar power from PV cells was available, rather than supplying it to the grid, and the advantages of V2G would be lost [30]. Since V2G can only work if the car fleet stands wastefully idle most of the day, it will at best be a transition technology. Unlike household energy storage discussed in Sect. 6.2, V2G will probably have at best a minor role to play; future ownership of vehicles is uncertain, but people will still live in buildings.

6.5 Smart Buildings

Smart houses (and smart buildings generally) are a necessary complement to smart grids. Similarly, smart electricity meters are needed for buildings to be considered 'smart' [17]. Here we will focus on smart houses and their potential role in reducing energy use and GHG emissions. In the coming era of intermittent energy supply, changing the *timing* of energy use may be as important for sustainability as reducing energy consumption.

We have already discussed the active role of householders in shifting energy-intensive *activities* to periods of high power availability/lower prices. Here we consider another important means for energy demand management: automated electric power demand shifting, an essential feature of smart buildings. Domestic energy-intensive appliances are of two types: those such as washing machines and dryers, and dishwashers, which are only operated intermittently, and appliances such as freezers, refrigerators, and domestic hot water services, which are run continuously. With Internet-connected smart appliances [39], the first group could be programmed to operate for minimum energy cost as an alternative to active householder operation. With continuously-run smart appliances, it would be possible to switch them off for short periods at times of high prices without any noticeable ill-effects [7].

Similarly, refrigerators and freezers could be run colder, and water heating units hotter, for short periods when electricity prices were low.

Another significant potential use for big data in buildings is for predictive maintenance. In Italy, software researchers analysed the year 2015 temperature, humidity, and electric power use data from the air conditioning and ventilation unit at a hospital [2]. They used data from the first half of 2015 to train the algorithms used, then applied it to the data for the second half. The algorithms were largely successful in predicting faults that did occur in the second half of 2015 and had only a 5% rate of false positives. Heating, ventilation and air conditioning represent about three-quarters of the total energy consumption of buildings in Europe [21]; hence any reduction in this load is significant. Already, in many Finnish apartment blocks, sensors have been installed to monitor temperature, humidity and air pressure in the apartments, and this monitoring enables the attainment of optimal conditions at reduced energy cost [2]. Predictive maintenance based on machine learning is also already proving its worth for industry as well.

Not only is the energy used by appliances in buildings important, but so is the energy used to construct and maintain the buildings over their service life. For example, replacing concrete and steel in buildings by timber can cut down on energy costs and GHG emissions. At the end of its useful construction life, the timber can then be combusted for energy, giving further GHG reductions [26]. Furthermore, attention to building design can not only save construction energy but even cut down on appliance energy use. Christian Calvillo and colleagues [6] have recently reviewed the literature on smart cities from such an integrated energy use viewpoint. They pointed out that if geographic information systems and 3-D modelling are used in building design, advantage could be taken of the local terrain to minimise occupant energy use, such as orientation for passive solar heating and light, and cross-ventilation from winds. Advantage can even be taken of sloping sites by partly burying the building to provide insulation and save on heating energy.

6.6 An Integrated View of Urban Energy Use

So far in this chapter, we have looked at several components of the urban energy system, while Chap. 5 discussed the energy aspects of transport. But just as climate scientists look at Earth energy flows [29], increasingly urban planners will have to look at urban energy flows as a system, if the aim is large urban energy reductions. All energy use in a city—whether from appliances, factories, power stations, street lighting, or vehicles—finishes up as waste heat. Here we look at how urban energy use could be viewed as a whole, so that, for example, the waste heat from one use could be utilised as an energy input to another. Energy cannot be created or destroyed, but it can be reused for purposes that only need lower-quality energy, just as the waste heat from vehicle engines is used to warm the vehicle interior.

The EU is currently funding research which aims to do just this [19]. The EU study is examining the ways that waste heat from such varied sources as underground railway stations, power sub-stations, waste incinerators, and even the heat from the wastewater of domestic baths and washing machines could be harvested and distributed to nearby residences. The potential is huge: a Danish study found that waste heat generated across Europe is more than enough to heat all its buildings [19]. With a city-wide system of temperature sensors, it would be possible to determine where large enough waste heat sources—and their heat output variation over time—were located to make their utilisation feasible, and, perhaps, in summer months, where waste heat generation should be reduced for the comfort of local residents.

Waste heat is also directly produced by thermal power stations—even for the most efficient power stations, more than half the input energy can be lost as heat. In principle, this waste heat could be used in district heating schemes, for hot water in all cities, and for space heating for cities in temperate and cold climates. At present, most power stations are designed to maximise electricity output for a given energy input. But if the waste heat is seen as an energy resource, rather than merely waste, then conventional power station efficiency is less important. For combined heat and power, the power stations would need to be located in the district because waste heat, cannot be feasibly transmitted by pipe more than a few km without excessive heat losses, unlike electricity, where transmission distances of hundreds of km are common. An apparent disadvantage is that such local power generating units would have much lower power output and electric conversion efficiency than larger units. This need not matter, as the ultimate test of efficiency is whether or not the combined heat and power (CHP) system has lower input energy needs and lower GHG emissions for satisfying a given set of energy services, compared with the present conventional systems, which use natural gas for heating, as well as electricity for its usual applications.

But such approaches may not be a sustainable solution, even if useful during the transition to a more environmentally sustainable urban future. As the world reduces its dependence on fossil fuels, the present dominance of thermal power stations will wane. Only renewable biomass power generation will have waste heat available for CHP systems. Waste incinerators—which can also be used for power generation—also produce waste heat, but with less waste production and more recycling expected in a sustainable city, this energy source might only be temporary.

Another possible source of waste heat for CHP schemes is from the combustion of methane tapped from landfills, which is in effect mining the energy from past urban waste. Use of landfill gas has two advantages for climate mitigation: it both substitutes biogenic methane for fossil fuels and also prevents emissions to the atmosphere of methane, an effective greenhouse gas. But, like methane from urban sewage plants, it can only ever be a minor urban energy source, and more recycling would see its potential decline over time. On the other hand, more use of timber for construction would eventually increase bioenergy use when burnt after its useful life as a construction material has ended.

An integrated view of urban energy use can also help avoid cases of sub-optimisation. For example, higher urban residential densities are often advocated as a means of reducing urban travel, and with it transport energy use and emissions (see Chap. 5). This approach is doubtless effective at very high levels of urban density, as indicated by the low per capita transport energy used in high-density cities like Tokyo and Hong Kong. The monetary and energy costs of urban infrastructure per building served are also lower because given lengths for roads, water pipes, and cables are shared by more users. And it also helps with district heating schemes, since it means more potential users within a given radius. But, as discussed in Chap. 5, there are other ways of managing urban travel demand which do not require the extensive modification of the presently low-density cities common in North America and Australasia.

The daytime urban heat island (UHI) effect is partly the result of the high levels of waste heat release per km^2 and the reduction in evapo-transpiration surface, both characteristics of cities. However, the energy savings discussed above from promoting higher densities may be at the expense of other areas of urban energy use—it may be a sub-optimal solution. High density living translates into high intensities of energy use per hectare, and high proportions of impermeable surfaces. All these features exacerbate the UHI effect and the need for air-conditioning. It also means that the ability to use *passive* solar energy—for heating, cooling, and providing natural light and ventilation to buildings—is curtailed. Suitable building and roof surface areas per capita for PV cell installation are also reduced. Higher densities also mean less vegetation, and the trees in urban parks, through evapotranspiration, can help cool the surrounding areas.

Unlike daytime UHI, most of the temperature rise from night time UHI results from the structural morphology of cities, and its impact on the release of stored solar energy from the surfaces of buildings at night [36]. Night time UHI can thus be reduced by changes to building heights, building surface materials—and their ability to both store and release heat—and 'sky view', which is a function of the building footprint. Since building density and building material properties also are essential for determining heating and cooling energy for buildings, many sensor measurements are needed for each urban location and time, to calculate the optimal path which would minimise total energy needs for the city. In existing fully built-up areas, major changes would be difficult but could be readily incorporated into newly developed urban areas, particularly in the cities of countries undergoing rapid urbanisation.

Finally, any new industrial plants, waste depots, and major transport routes should be sited to both minimise pollution for residents (whether from air, noise, or smell) and total transport distances, perhaps by co-location of complementary industries, as suggested by industrial ecology [42].

6.7 Discussion: Energy and Urban Sustainability

Caution is still needed to make sure that even an integrated approach to urban energy use as discussed in Sect. 6.6 does not shortchange other aspects of an ecologically sustainable and liveable city. Reducing total energy use will surely be necessary for climate change mitigation, but it must occur in such a way that is not at the expense of other urgent concerns such as environmental amenity, health, and equality. Just as not all big data applications will necessarily save urban energy (as shown for

AVs), so not all options for real urban energy savings can be taken up, because of conflicts with urban well-being. The aim clearly must, therefore, be to derive the greatest amount of *energy services* from each unit of primary energy used and to maximise use of passive solar energy.

Finally, the energy requirements of big data itself need to be monitored [32]. Some researchers have argued that the electric power costs of Internet transmissions may themselves be significant. According to Vlad Coroama and Lorenz Hilty [8], published estimates for energy intensity over the decade 2000–2010 have been in the range 0.0064 to 136 kWh per gigabyte of data transmitted, although estimates have declined over time. Another reason for this four orders of magnitude variation found was whether or not the power consumption of end devices was included. If, as seems reasonable, it must be included for a full assessment, the energy costs are significant and need to be reduced.

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