URBAN ENERGY SYSTEMS

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I Introduction

This paper takes the conference at its word and looks at the prospects of a factor 10 decrease in urban energy consumption. Just to make matters more interesting it does not assume that the city is full of Factor 10 citizens, just serious entrepreneurs. A sketch of points from urban theory is followed by a discussion of the theoretical optimum contribution of *urbanization* to city and transport use.

II Organizing Features of Cities

Since spatial issues are so important to the engineering of cities a few general remarks are in order. Cities form because people find they can do something better together than apart. They fill space because other things are worse when shared. As Wilson showed in the 1970's this tension creates the conventional exponential density distribution centred on the central business district. Citizens predominantly live out the same lifestyle scenario for practical and social reasons. Given that travel is wasted time exchanged for the privilege of access it is perhaps not too surprising that Zahavi found that urban travel takes up around an hour a day wherever you are. So speeding up the commuter's journey just creates a new equilibrium of travelling longer distances. Fast travel simply flattens urban density. At some point (usually quoted at around 20 – 25 persons/hectare) urban transit systems take too long to collect travellers to fit the paradigm, and this can be taken as one sense of suburban (in contrast say to 'commuter towns'). Cities systems have a pulse rate in the sense that they try to bring people very close together to do business during the day and then separate them out again as far as is possible for personal life in the evening.

City size ranks with extraordinary precision to the Zipf-Mandelbrot law. This implies that cities are in some sense 'scale-free' and grow by 'over-writing' themselves. As a consequence we should be careful not to overplay a city's 'legacy'. Cities seem perfectly able to re-invent themselves time and time again. Nor should we overplay the 'opportunity' of a Green field site. It is very likely to lose its advantages very rapidly as the site grows. The UK's New Towns of the 1960's are often in a worse state now than the Old. It also rather suggests that the forces that form cities are much stronger than master plans and mayors! Portugali has gone as far as to suggest that cities are self-organizing systems. If they are then it may explain why they are so difficult to handle in reductionist analysis. It is not that we have no theories of urbanization consistent with the facts. So many things correlate with so many others we have far too many theories!

There are two density distributions that are exceptions to the exponential, both new in the 20th century and caused by very rapid growth. In several developing world cities the influx of rural immigration is so large, driven by the pressures of over population and civil war that dense peri-urban areas cluster around the older city cores. These new citizens are effectively living off of the core's waste streams with occupants percolating into inner city areas only as real jobs are created. If it were not for the often extreme poverty these cities would be the exemplar of re-use and recycle. The other extreme is the structure-free city characterized by cities like Atlanta (more of that no doubt from Bruce Beck) or Phoenix (which already covers an *area* greater than LA). By growing without structure, these cities have enlarged much faster than any over-writing could have achieved. They essentially have no central district, just very many districts linked by high speed connections. Interstate 10 that serves Houston is 22 lanes wide and a kilometre across at its widest point. Houston has a density around 10 persons per hectare compared with Mumbai at 400.

Energy supply just occasionally determines a city location or form. For the medieval city there was a plausible limit to circumference caused by congestion in getting biomass in (the problem increases in proportion to the radius), but it was probably pre-empted by the constraints of Zahavi's constant. The big European cities of the 19^{th} century circumnavigated the problem by using 'sea coal' brought up stream on the navigable rivers that underpinned their economy. A constraint again seems to emerge for large cities at the end of the 19^{th} century in managing horses as the main source of motive power. The arrival of energy grids and internal combustion removed the constraint altogether. Microclimates did matter in the design of 17^{th} century cities but now that is a largely forgotten art. Transport connections make a very big impact, but energy consumption is otherwise largely a resultant property of what a city is about.

III How to Measure Urban Energy

Urban energy discussions tend to mix together two quite distinct issues. Most people live in cities and so most energy consumption takes place in cities. However some of that consumption would have occurred wherever citizens lived. A domestic refrigerator takes little notice of whether it is in an urban, suburban or rural kitchen. Roof insulation over a room at 21C does the same job where ever it is. There is not much point blaming London or Paris for large energy consumption when they contain a large number of energy consuming units that would have consumed energy where ever they were located. London has a population larger than Sweden and an economy larger than Austria so it is not altogether surprising that it has a carbon footprint considerably larger than the M25. A barely sufficient African family farm needs about a hectare of land, an area taken up by about 50 Londoners. Neither is there much point blaming cities for having more prosperous residents. They probably consume more energy when at their country estate than they do in their Mayfair flat. What is interesting is how urbanization changes, or could change, the average daily consumption.

Statisticians love to measure urban energy in delivered energy units, presumably because they are easy to count from utility bills. Tracing back the implications of delivered energy to the primary energy input usually gives figures closer to the relative cost of each energy type to the consumer. But as Hammond has pointed out, if you really want to look at ambitious reductions there is something to be said for taking the process engineer's view and use exergy.

IV Exergy Analysis

Exergy corresponds much more closely to what we mean by 'energy' in everyday speech. We 'run out of energy' or 'conserve energy' despite being told at school that energy is conserved. Exergy is formally the *maximum* theoretical amount of mechanical work that can be extracted from an energy source. Thus it takes into account that if the source is at absolute temperature T, the thermodynamic limit on the work extracted reduces the usefulness of the source by a factor $(1-T_o/T)$. A kilojoule stored in steam at 100C is much more useful than a kilojoule stored in tepid bathwater. Similarly energy demands can be classified by their temperature requirement by converting them to the pure work or exergy required to pump[1] heat from ambient temperature to the required temperature.

The ratio of the exergy demand to exergy supply is the system's exergetic efficiency and the difference a measure of the entropy being generated in the system. Minimizing entropy generation is a standard design algorithm in process engineering (pioneered by Bejan), and will have been employed in a large boiler installation. Exergy analysis would spot immediately that electric resistive heating was disastrously inefficient (about 3% if the system is delivering heat at 20C). It would be much tougher on electricity use in general than on space heating. Sometimes it turns our conventional ideas on their head. So the advantage of CHP is not to utilize the waste heat of power generation (because

[1] An example of an (imperfect!) heat pump is an air conditioning unit but with the focus on the heat delivered rather than extracted.

the waste exergy of the tepid water in a conventional plant is already low) but to recover some of the enormous exergy loss in a boiler where a gas flame at 900C is being used to deliver only water at 80C.

The exergy analysis treats the city as a process. The reference city is then one where work is supplied by perfect Carnot heat engines fed by primary energy entering the city. Where necessary heat pumps extract heat from ambient or discharge streams to meet thermal needs and without meddling with demand per se. To get the flavour of what such an analysis might expose I have taken the Mayor for London's Energy Strategy data (but taking out road transport and aviation for the moment). I have then dismembered it on the lines of the national exergy analysis undertaken by Hammond which allocates to different delivery temperatures energy supplied to the conventional industrial, commercial and domestic sectors. Hammond's data draws heavily on the BRE factfile. We get (roughly!) the following table:

PJ per year	Energy	Exergy
Total Primary Exergy Used	650	650
Final Use		
Power	60	60
High Temp Demand	11	7
Medium Temp	63	35
Low Temp	260	60
		~160

So without making any changes to demand per se, but focusing on thermodynamically efficient demand we get an exergy bench mark of 160 PJ/year. London is running at about 25% of theoretical efficiency, and we have not even addressed how the demands themselves can be improved. All the demands will have hot discharges (not to mention the residue exergy of the material waste streams) which suggests that we could 'easily' get to 10%!

V And So?

The exergy analysis, as usual, is inviting us to look out of the box. The inefficiency is coming from mismatched temperatures and they are cured, at least in process industry, by heat recovery systems and inter-mediate temperature storage. Some of the earliest 'factor 4' examples come from using this technique. Assuming resistive heating has been removed altogether, the urbanization advantage is that the demands are feasibly within reach of each other for cross-optimisation. Many buildings try some form of optimization but seldom seek to gain the advantages of collective optimization. There are few cases where different networks like water and electricity have been tightly optimized. Where something like this system has been explored on large single-owned complexes, the designer immediately jumps to using the road space as a rationalized resource for distribution mains.

I promised at the beginning a proposal based on entrepreneurs. Suppose then we privatized the street and left the owner to make the most of the cross-optimisation opportunities? Most cities are a bizarre mixture of high technology buildings and strips of dirt with tarmac tops. Something like 20% of a city's surface is wastefully managed in this way. The privatized street then provides services to its curtilege but makes its profit on cross-optimization. Water pressure has to be reduced for example as it is distributed through the city. May be the 'service lane' owner could install turbines rather than pressure reducing valves and sell the power locally?

VI Urbanization and Traffic

I left transport energy out of the table, and it is time to see what urbanization could do for transport energy consumption. A characteristic length scale for a city is given by the inverse square root of its occupation density. In a featureless city this would be proportional to the average interpersonal separation. Since we would expect this distance to be traversed at the Zahavi interval, it follows that the lower the density the higher the average speed. Since the miles per gallon vary only slightly at US freeway speeds (not Autobahns!) fuel consumption is simply proportional to trip length. We do indeed see a roughly quadratic relationship between density of sprawl city and vehicle energy consumption. But European cities while usually better than the best of the sprawl cities show little clear density dependence. The answer appears to be that the effective vehicle efficiency starts to drop off quadratically, and what is gained by the shorter journey in the denser city is lost by the slow average speed.

Other papers will address what can be done to the vehicle. The predominant problem for the urbanization component of vehicle transport is the interaction between vehicles on uncoordinated journeys. Creating an equivalent of the exergy analysis is not straightforward but it is a fascinating question whether in the presence of perfect knowledge there would remain an intrinsic interference factor between vehicles. The analysis would not presume to make dense urban traffic move faster, but simply not use its brakes! If we could simply extend the sprawl relationship 'to the origin' we halve European city transport energy. Since this outcome is characterized by predictable journey times it is a premium solution that an entrepreneur could market *if* we had the software!

VII Reflections

This paper set out to take the conference at its word and look for a factor10 improvement. I have purposely not discussed the measures that could take place at each unit of consumption where actions would have largely the same effect whether the unit was rural or urban. Needless to say the ideas proposed are totally exploratory. People who work in city systems are necessarily practical people, and if factor 10 had been out there they would have no doubt realized it. But practicality has its disadvantages. We are promised serious recapitalization of the energy sector over the next 20 years and the R&D programmes on the supply side are already exploring 'way out' options like carbon capture and even fusion. Yet just the two options proposed here of extending heat recovery and storage technology and exploring massive optimization techniques look as if they could yield almost the same impact at about the same risk. Nor should we forget that things are changing in cities. Because of the increased use of imbedded sensors and remote sensing cities know more about themselves than they have ever done before. Techniques are being developed that enable this vast data stream to be patched into effective control models. Cities are where most innovations occur so why not in energy demand?

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