Identifying lessons for energy-efficient cities using an integrated urban energy systems model

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25 February 2010

Abstract

Energy consumption in urban areas is increasingly recognized as an important source of global greenhouse gas emissions. Modelling efforts to date have identified significant potential savings in individual sectors, such as transport or district energy systems, but there have been few attempts to model urban energy systems in a holistic manner. This paper presents SynCity, an integrated toolkit of optimisation and simulation models for urban energy systems, and applies it to three analyses. First, an assessment of urban form is made using Monte Carlo analysis to highlight the potential costs of planning restrictions on the maximum density of urban areas. Second, the efficiency of different energy system configurations are explored for a range of cities to reveal that cities need to be able to access a variety of technology sizes in order to achieve cost and energy savings. Finally, all three models within the SynCity system are used to evaluate the individual and joint effects of urban density, quality of the built environment, and energy systems design, suggesting that taken together, these factors can achieve primary energy savings of 41% and energy system cost savings of 49%. The results highlight the importance of designing holistic long-term urban energy planning frameworks and supportive market structures.

1 Introduction

Cities account for approximately two-thirds of global primary energy consumption and 71% of energy-related greenhouse gas emissions (IEA, 2008). Driven in part by increased rates of urbanization in the developing world (UN, 2008), these figures are expected to increase over the next two decades. Policy makers,

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utility operators and other stakeholders therefore need a clear understanding of the factors which shape urban energy use so that they may effectively direct investment to achieve improved efficiency, without sacrificing the economic and lifestyle benefits that make cities attractive.

Energy demand patterns vary widely from city to city, across countries and continents. Cities in North America, Europe and Australasia typically consume less per capita than their respective national averages. However in China, for example, higher incomes and improved access to electricity and other energy services result in urban per capita consumption almost twice the national average (IEA, 2008). Similarly the breakdown of energy consumption by sector varies: in high-income cities, the split is typically 57% buildings, 15% industrial and 28% transport; in medium-income cities, it is 24% buildings, 22% industrial, and 54% transport (UN Habitat, 2008). These differences can be explained by climate, economic structure, technology, culture and other factors.

This diversity poses a significant problem for policy-relevant urban energy modelling. On the one hand, detailed studies of urban energy systems (or parts thereof) can provide valuable insights into the choices faced by a particular city or consumption sector. Table 1 highlights a few studies of this kind, illustrating both the range of applications and the often significant data requirements or technical expertise required to use each model. On the other hand, although this specialization enables the quirks of local geography, economics or technologies to be captured, it does make it difficult to quickly transfer the techniques and results to other urban areas or to provide an overview of the urban energy system across consumption sectors. A holistic urban energy model that can be easily applied to multiple contexts and assess consumption in multiple sectors could therefore be valuable for identifying general policy lessons.

Table 1: A selection of urban energy modelling studies.

Citation	Technique	Notes
Lin and Feng (2003)	Non-linear programming	Optimises layout of urban area, in part based on transport energy
Brownsword et al. (2005)	Linear programming	Identifies cost-effective energy or CO_2 reduction targets for buildings
Parshall et al. (2009)	GIS-based inventory	Uses emissions database to estimate urban energy consumption
Girardin et al. (2010)	GIS-based optimisation model	Focuses on district heat and cooling in Geneva
Connolly et al. (2010)	Review of 37 studies	Highlights different scales of energy integration models and difficulty identifying an all-purpose ‘ideal’ model.

This paper presents a series of case studies using an integrated strategic urban energy model known as SynCity, developed by the BP Urban Energy Systems project at Imperial College London. In Section 2, I present an overview of the methodology which consists of optimisation and simulation models designed to capture the major determinants of urban energy consumption. Three case studies using the tool are then presented. The first two use individual component models of the SynCity system to explore the impact of planning restrictions on urban density and the scale of energy system technologies. In the final analysis, the entire model suite is used to evaluate the effects of three major determinants of urban energy demand: density, quality of the built environment, and choice of energy supply systems. The concluding section then highlights the main recommendations arising from the work and considers how the methodology and results might be extended.

2 Methodology

SynCity ("Synthetic City") is a software platform for the integrated modelling of urban energy systems, developed at Imperial College London and supported by funding from BP. The goal of the tool kit is to bring together state-of-the-art optimisation and simulation models so that urban energy use at different stages of a city's design can be examined within a single platform. It is primarily a strategic design tool; that is, it allows interested stakeholders to quantitatively examine the consequences of decisions and assumptions but it does not replace the function of a detailed engineering design tool.

2.1 Software architecture

The SynCity framework consists of three major components.

The first is an ontology (formal data model) for urban energy systems. Implemented using Protégé (SCBIR, 2009), the ontology provides consistent definitions for key urban energy system components such as resources (e.g. electricity, gas), conversion processes (e.g. gas boiler, combined heat and power units) or infrastructures (e.g. buildings, transport networks). It serves the dual purpose of providing a user interface for the input of new data as well as clearly defining a consistent class structure to assist with software design and model integration.

The second component is a Java application programming interface (API). This code library allows users to load objects from the ontology, assemble them into modelling scenarios, and coordinate the running of one or more sub-models. The API also has tools for visualizing the results and generating summary reports. At present, there is no graphic user interface front-end for the API and so users require some knowledge of Java to write their models.

The final component is a series of sub-models, described in detail below. These models can be run from within the API, either individually or as part of an overall analysis, or as stand-alone models.

2.2 Sub-models

There are currently three core models within SynCity:

- a *layout model* which determines the optimal configuration of buildings, service provision and transportation networks;
- an *agent-activity model* which simulates the activities of heterogeneous agents acting within a specified urban layout in order to determine temporal and spatial patterns of resource demand; and
- a *resource-technology network model* (RTN) which calculates the optimal configuration of energy conversion technologies and supply networks.

A fourth component, a *service network model*, is currently in development. This model examines the operational performance of integrated resource distribution networks. Early work in this area can be found in Acha et al. (2010a) and Acha et al. (2010b).

The layout model

The layout model is a mixed-integer linear programming model which seeks to satisfy urban demands for housing and activity provision, while minimizing energy demand from buildings and transport. Users specify average visit rates for each activity type and the model will determine the optimal location for housing, commercial buildings, activities, and transport networks (Figure 1). The model is implemented with the General Algebraic Modelling System (GAMS) and objective functions include minimizing cost, energy consumption or carbon emissions.

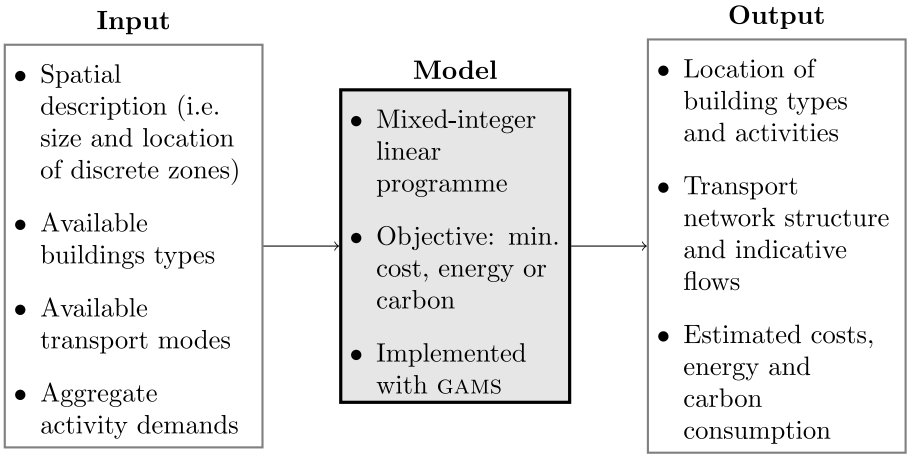


Figure 1: Schematic for the layout model.

Previous work in this area has used non-linear programming formulations (Feng and Lin, 1999; Lin and Feng, 2003) or, much earlier, linear models on slow hardware (Barber, 1976). The result is that these models are unable to handle large problems (i.e. on the order of hundreds of cells and tens of activities). The present mixed-integer formulation is a compromise, providing better performance than a non-linear formulation but more representational fidelity than a linear model. For example, by adding integer variables, each cell within the city can be occupied by a unique activity and the model can also determine network routing, using binary variables to represent the presence of a connection between two cells.

The layout model is used as the first stage of an urban energy assessment. For a greenfield site, it can determine a low-energy master plan and transport network automatically given basic data about the site. However if the project is a re-development, or an already planned city, users can manually specify either all or part of the layout before running this model or the subsequent agent-activity model.

The agent-activity model

The agent-activity model is a simulation model designed to estimate the resource demands of a population living within a particular city layout. In other words, if the layout model estimates the aggregate energy consumption, the agent-activity model attempts to simulate the actual consumption based on an urban population's diverse daily activities. This type of modelling has primarily been within the domain of transport modelling (Sivakumar, 2008). Such models use various choice modelling approaches to assess a citizen's travel patterns, which requires extensive input data to parameterize the models. SynCity's agent-activity model currently adopts a simple four-step modelling process to capture some of this choice behaviour but with fewer data requirements.

Briefly, the model operates as follows. First the model creates a synthetic population of individual agents with random characteristics such as gender and education. Agents are grouped into household ensembles and assigned to jobs and dwellings. The model then loops over 16 indicative time periods representing two seasons (summer, winter); two day types (weekday, weekend); and four time intervals during the day. For each interval, a probabilistic four-step transport model is used whereby citizens select an activity (e.g. work), an activity provider (e.g. their employer), a transport mode (e.g. bus or car) and a travel route. The agents then move around the city and perform their planned activities. The result of this simulation is a spatially- and temporally-explicit pattern of demands for different end-use energy resources, such as electricity or heat (Figure 2).

Again because of the modular nature of SynCity, if resource demands for a city are already known, the user can input these data manually and proceed directly to the resource-technology network model.

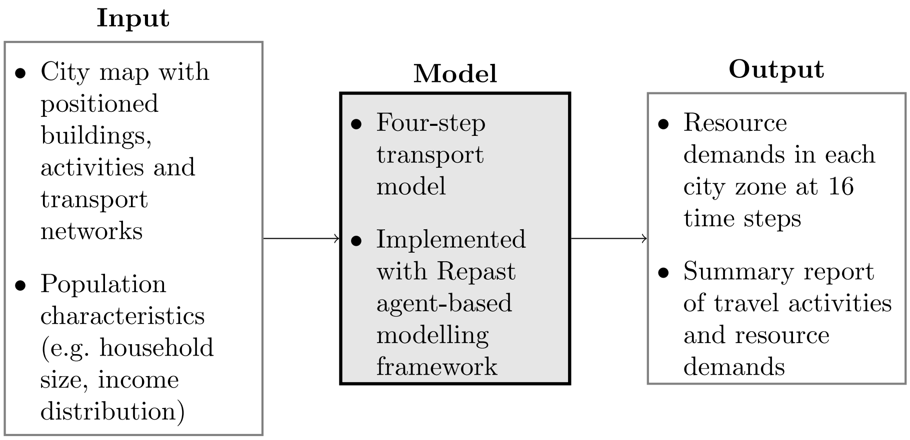


Figure 2: Schematic for the agent-activity model.

The RTN model

The resource-technology network (RTN) model is also a mixed integer linear programming model. Its aim is to determine the optimal configuration of energy supply technologies in order to meet a given pattern of demand. The objective is to minimize the total cost of the energy supply system as comprised of the annualised cost of capital equipment (e.g. boilers, turbines, and distribution networks) and the annual cost of imported resources necessary to operate the system (e.g. supplies of gas and electricity). Users specify the full suite of possible technologies at the outset and the model will return the lowest cost system configuration (Figure 3).

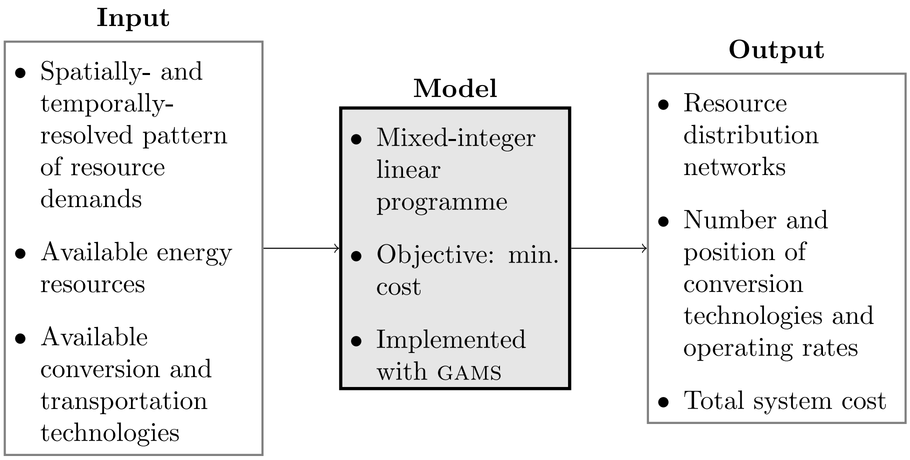


Figure 3: Schematic for the resource-technology network model.

There has been extensive previous work in this area, although as with the layout model, our model formulation is slightly different. Earlier studies often use linear-programming formulations and examine single time periods (e.g. Bruckner et al., 2003; Henning et al., 2006). This ensures that the models solve quickly but it fails to capture some essential characteristics of an urban energy system. In particular, the RTN model simulatenously optimises the supply system over multiple time periods (e.g. peak and average demands) and across all resource networks (e.g. electricity, gas, etc.), again using binary variables to determing network routing at the same time as identifying the overall technology mix and performance.

The model's formulation is based primarily on a resource balance:

$$P_{rit} + Q_{rit} + I_{rit} - E_{rit} - D_{rit} = 0 \quad \forall rit$$

where P_{rit} is the net production rate of resource r in zone i at time t, Q_{rit} is the net resource inflow from all other zones within the city (i.e. internal transport), I_{rit} and E_{rit} are the rates of import to and export from the city respectively, and D_{rit} is the resource demand. As can be seen from this equation, a number of energy supply strategies are able to satisfy the resource balance. Resources can either be imported directly from outside the city; they can be transported from other locations within the city; and they can be produced by converting other resources. (The model also allows for storage processes, although these technologies are not considered in the present paper). This formulation therefore enables complex energy supply chains to be assessed simulataneously. For example, Keirstead et al. (2009a) examined urban biomass supply strategies with the RTN model, incorporating imported forest residues, local wood chip production and conversion to heat and power.

2.3 Summary

SynCity is a software toolkit that can be used to analyse different facets of urban energy consumption, primarily within an integrated analysis. However each of the sub-models discussed above can also be run on its own, allowing for customized applications as well as sensitivity and uncertainty analyses; this type of application will be considered in the following two sections. The modular nature of the software also allows a range of problem types to be considered from greenfield master planning exercises, through to retrofit and operational studies.

3 Urban form: quantifying the benefits of high-density housing

In this section, the layout model is used to explore the impact of planning restrictions on high-density housing. This work arose from an earlier case study (Keirstead et al., 2009b) which revealed that the lowest energy urban layouts often rely on densities that are both higher and more homogenuous than a developer may wish to use in practice. The aim of the present analysis is therefore to estimate the energy "penalty" of limiting the coverage of high-density housing to a certain fraction of total housing.

3.1 Set up

For this analysis, a city composed of 16 ha. cells, arranged in a 10×10 grid, has been assumed. The layout model can satisfy residential requirements using three housing types at low (20 dw/ha), medium (35 dw/ha) and high (65 dw/ha) densities and commercial buildings for work and shopping must also be provided.

The experiment was configured as a Monte Carlo simulation with 1000 runs. In each scenario, random values for key parameters were drawn from the following uniform (U) distributions, using a Sobol' low-discrepancy sequence:

- Total population, $U(180, 240\,000)$ people
- Maximum high-density housing fraction, $U(0, 1)$

Of the 1000 simulations, only 461 were feasible due to the interaction of the high-density housing fraction, x_{hd}, and the total population variables. For example, in order to house the maximum population (240 000), the entire city would need to be filled with high-density housing (i.e. $x_{hd} = 1$). As the x_{hd} parameter varies between 0 and 1 and some cells are required for commercial buildings, the model is often unable to provide sufficient housing for large populations using low- and medium-density dwellings on a fixed amount of land.

3.2 Results

Each feasible configuration can be summarized by the total final energy consumption per capita. Comparing these results for different values of the x_{hd} parameter allows the energy implications of a planning restriction on high-density housing to be assessed. Such a restriction may be implemented by policy makers to ensure a certain level of heterogeneity in the urban form (e.g. for aesthetic or liveability reasons) or to satisfy capacity constraints on service provision (i.e. insufficient drainage).

First, a baseline was defined by calculating the average energy consumption per capita for all model runs with a high-density housing fraction of 10% ± 2.5%; this gives a reference value of 76 GJ per capita.

A linear model was then fit through the data (Figure 4) indicating that, relative to a base case of 10% maximum allowable high-density housing fraction (i.e. $x_{hd} = 0.1$), every 1% point increase in the maximum allowed fraction of high-density housing will reduce per capita total energy consumption by 0.35% ($r^2 = 0.32, p \ll 0.0001, df = 343$ after removing outliers). In other words, if a city decided to allow 20% high-density housing instead of only 10%, total energy consumption per capita could be reduced by approximately 3.5%.

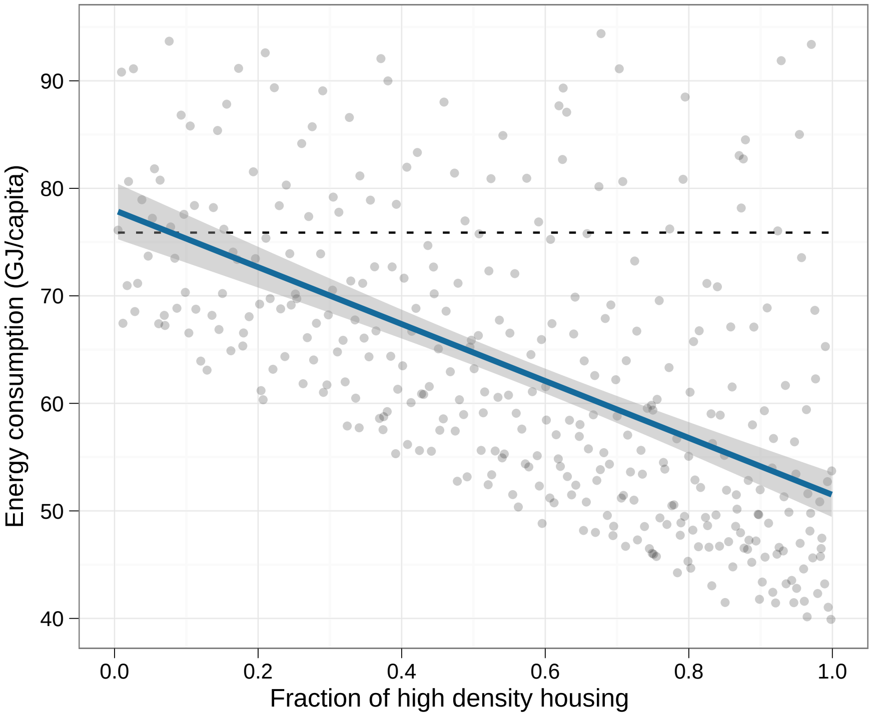


Figure 4: Linear regression showing final energy consumption savings achieved as the maximum allowable high-density housing fraction increases. The dashed line represents the 10% baseline; the shaded area indicate the 95% confidence interval for the regression line.

4 Energy systems: choosing an appropriate scale for energy supply technologies

The resource-technology network model allows multiple energy supply technologies to be considered in a single analysis. This means that technology classes can be compared with each other (e.g. fossil-fuel versus renewable energy systems) but it also means that similar technologies at different sizes can be assessed. In this section, the performance of combined heat and power (CHP) technologies at various scales are compared.

4.1 Set up

As the experiments use only the RTN model, a simple algorithm was used to generate a spatial pattern of heat and power demands. Grid cities comprised of 16 ha. cells were assumed, ranging from 4×4 to 16×16 cells (approximately 10000 to 200000 residents). For each grid city, it was assumed that dwelling densities vary linearly from the centre (with some random variation) from a maximum of 65 dwellings per hectare to a minimum of 10 dwellings per hectare. Taking the average household size to be 2.3 people, heat and power demands were then calculated using London benchmark data (DECC, 2008). A typical pattern of demand is shown in Figure 5.

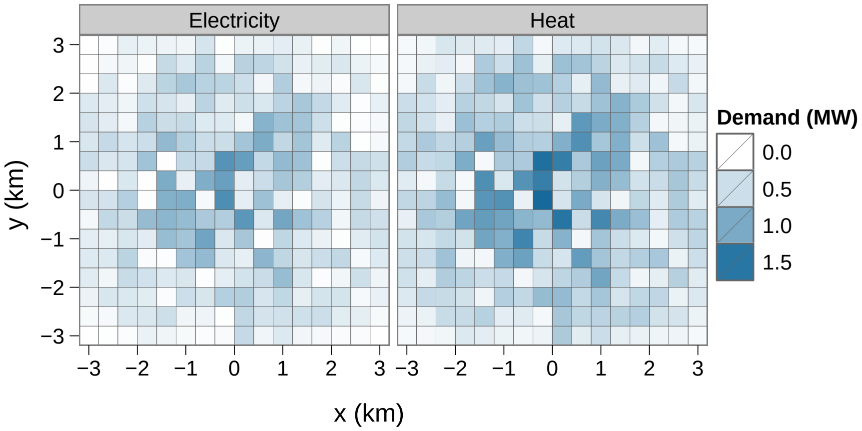


Figure 5: An indicative pattern of resource demands for a 16×16 grid city.

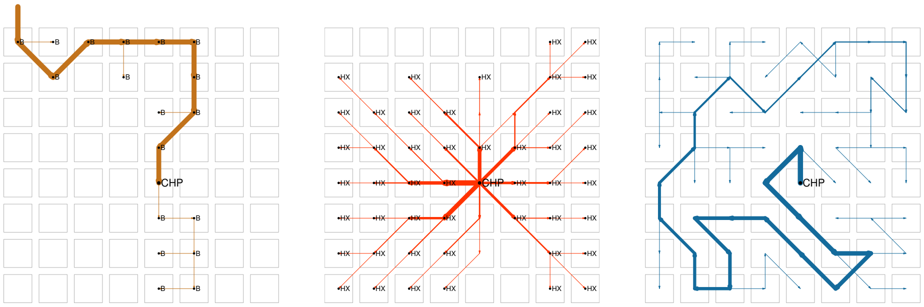
Each grid city was then run with five different technology suites: boilers only (heat provided by 26 kW domestic gas boilers), small-scale CHP (1 MW_e CHP, with heat exchangers and gas boilers), medium-scale CHP (10 MW_e CHP, with heat exchangers and gas boilers), large-scale CHP (100 MW_e CHP, with heat exchangers and gas boilers), and all technologies (boilers, heat exchangers and all three CHP sizes). Boilers were included in all of the CHP scenarios to ensure feasibility, as the model was constrained to prevent excess electricity being exported from the urban area.

4.2 Results

Each model solution consists of a unique combination of technologies and resource distribution networks; Table 2 and Figure 6 present sample results for the 8×8 grid city. Note that in all of the technology scenarios, except the large CHP case, the chosen technologies are operating very close to their rated maximum capacities. This occurs because the RTN model considers the *aggregate* supply and demand within a cell and so the output from, for example, a gas boiler can effectively be shared between all households in that cell. Future versions of the model will introduce further constraints on such technologies. The figure shows how the district heating system penetrates into the central areas of high demand but leaves outlying areas of low heat demand to be serviced by gas boilers. Note however that the networks are not designed for robustness or resilience.

Table 2: Summary of technology combinations for the 8×8 city scenarios. CF = capacity factor, i.e. average operating rate as % of maximum operating capacity.

Scenario	Technology	Number	CF
Boilers	Gas boiler	1571	98
Small CHP	CHP units	30	98
	Heat exchanger	1220	98
	Gas boiler	64	97
Medium CHP	CHP units	3	100
	Heat exchanger	979	94
	Gas boiler	407	99
Large CHP	CHP units	1	31
	Heat exchanger	953	98
	Gas boiler	396	97
All techs	Small CHP	6	67
	Medium CHP	3	89
	Large CHP	-	-
	Heat exchanger	987	98
	Gas boiler	350	97



(a) Gas (b) District heat (c) Electricity

Figure 6: Resource distribution networks and technology locations for the large CHP 8×8 city scenario. B = boiler, HX = heat exchanger, CHP = 100 MW CHP. The city is ultimately powered by a large flow of imported gas, visible in the upper left corner of Figure 6(a).

The modelled scenarios can be evaluated as a whole by considering their cost and energy efficiency. Figure 7 shows both of these objectives. The key observation is that the Pareto optimal solutions, i.e. those that minimize both cost and energy efficiency, are typically represented by the "all technologies" scenario. The medium-scale CHP scenarios also perform well, as this technology's 10 MW_e rated capacity corresponds closely to the demands in the various cities studied here (ranging from 3 to 57 MW total).

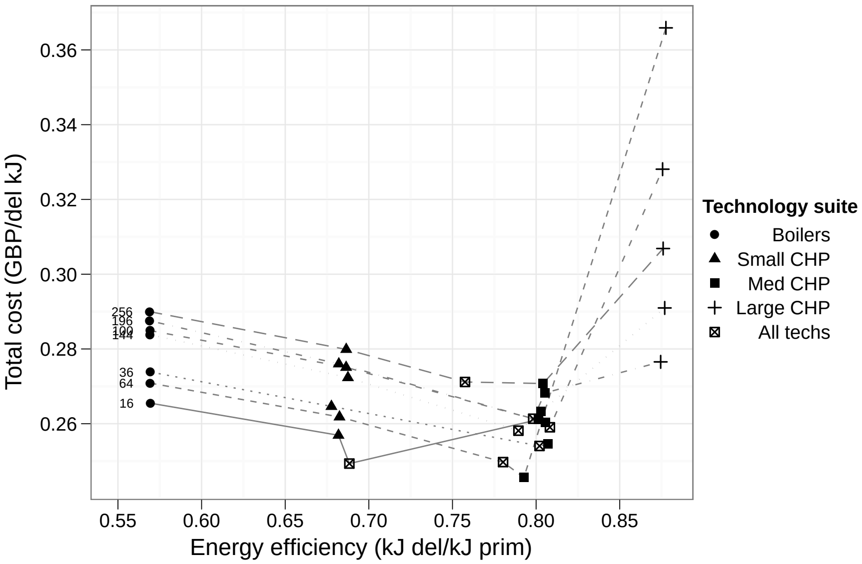


Figure 7: Summary of cost and energy-efficiency performance. Line types and numbers represent city size (cells).

The results suggest two lessons. The first is that efficient urban energy systems rely on a mix of technology scales. Even the well-performing medium CHP scenarios require some gas boilers to satsify areas of low demand. If it is assumed that the gas boilers case represents a business-as-usual situation, then these optimal mixed technology scenarios offer cost savings of approximately 10% and energy savings of 30%. Secondly, the results indicate that the largest technology required by a city will, of course, depend on its level of demand. For policy makers, this means that delivering efficient energy systems may require integrating very large power systems within the urban fabric. Copenhagen is an example of this with the 810 MW_e Avedøre plant (Dong Energy, 2010) located approximately 10 km from the city centre, alongside many other smaller urban plants. Other cities however, such as London, rely primarily on imported fuels and may be reluctant to (re-)introduce plant of this size for reasons of local pollution or because of a lack of district heating infrastructure with which to harnass the benefits.

5 An integrated analysis of three urban energy factors

Each of the case studies above looked at a single model within the SynCity system. In this section, the entire framework will be run from start to finish: first, the layout model to determine the urban form; then the agent-activity model to simulate associated resource demands; and finally, the resource-technology network model to assess energy supply strategies.

5.1 Set up

The analysis consists of six model scenarios that are collectively designed to assess the effect of three major determinants of urban energy use: layout (i.e. urban density and facility location), the quality of the built environment and the use of district energy systems. As Table 3 shows, the factors are varied one at a time so as to isolate the effect of each variable. A detailed description of each factor is provided below.

Table 3: Scenario configurations. Please see text for a full explanation.

Scenario	Built fabric (SAP rating)	Density archetype	Layout	Energy system
Current practice	50	UK	Mononuclear	Household
Efficient buildings	100	UK	Mononuclear	Household
Optimised layout	50	Japan	Optimised	Household
Sparse layout	50	US	Optimised	Household
Distributed energy	50	UK	Mononuclear	CHP
Optimised	100	Japan	Optimised	CHP

Built fabric The quality of the built environment is represented by the UK Standard Assessment Procedure rating (SAP, BRE, 2009). A SAP rating of 50 corresponds approximately to the current standard of London's housing stock (GLA, 2004); the scale's highest value of 120 represents a net energy exporting dwelling, whereas the chosen "efficient buildings" rating of 100 approaches the Passivhaus standard of 15 kWh/m^2 year.

Density archetype The layout model can choose from a range of residential housing types, each with a different density and floor area. Three density archetypes are used here. The "UK" type describes densities of 20, 35 and 65 dwellings per hectare and medium sized dwellings (60–200 m^2). The "Japan" type represents higher densities of 50, 75, and 100 dwellings per hectare and smaller dwellings (30–100 m^2). Finally, the "US" type represents the low density sprawl found in many North American cities with housing densities of 5, 10 and 20 dwellings per hectare and associated larger floor areas of (200–300 m^2).

Layout In cases where the layout is not optimised, a simple mononuclear city has been assumed. In the optimised cases, the layout model can choose the position of dwellings and activities subject to key constraints, such as ensuring that all required services are provided and there is adequate housing for the entire population.

Energy system The energy system is modelled as either a (UK) "business-as-usual" system, with heating provided at the household scale by gas boilers or electric heaters, or a CHP-based system with gas-fired combined heat and power systems at three different sizes (1, 3, and 6 MW thermal) and an associated district heat network.

In all cases, the city is represented by an 8 × 8 grid of uniform squares, each with an area of 16 hectares and a total population of 20000. Von Neumann neighbourhood connectivity has been assumed between the cells (i.e. Manhattan style blocks with no diagonal connections) and four activity types are modelled: shopping, service-based work, education, and leisure.

5.2 Results

Each model run calculates four headline results: primary and final energy consumption per capita, carbon emissions per capita, and energy system costs. These figures include energy consumption from the commercial and domestic sectors, as well as an estimate of transport energy consumption based on simulated passenger-kilometres, referenced to London's actual per capita transport energy consumption. Energy system costs include the annualised costs of capital equipment (at 6% over 25 years) and annual fuel costs. In order to validate the results, a baseline was established using regional energy consumption data for London (DECC, 2008), national statistics for carbon emissions factors (Defra, 2008) and the primary energy efficiency of electricity (DECC, 2009). Table 4 summarizes these results.

Table 4: Summary of modelled scenarios. All figures represent annual values.

Scenario	Energy consumption GJ/capita		Carbon emissions (t CO_2/capita)	Energy system costs (million £)
	Primary	Final		
Current practice	105.4	79.1	5.7	17.8
Efficient buildings	79.1	55.7	4.4	12.6
Optimised layout	72.0	51.4	4.0	12.1
Sparse layout	139.9	106.7	7.6	22.7
Distributed energy	98.5	90.7	5.2	14.9
Optimised	61.5	55.7	3.3	9.0
London reference	104.2	72.4	5.97	

Energy analysis

Figure 8 provides a graphical summary of the energy results, where demand has been broken down into buildings (domestic and commercial), transport and supply (i.e. primary energy losses). It shows that there is good correspondence between the London baseline and the "current practice" SynCity reference scenario, thus providing validation of the methodology. The figure also indicates that each of the three variables – quality of the built environment, density, and choice of energy system – has a significant impact on the overall performance of the urban energy system.

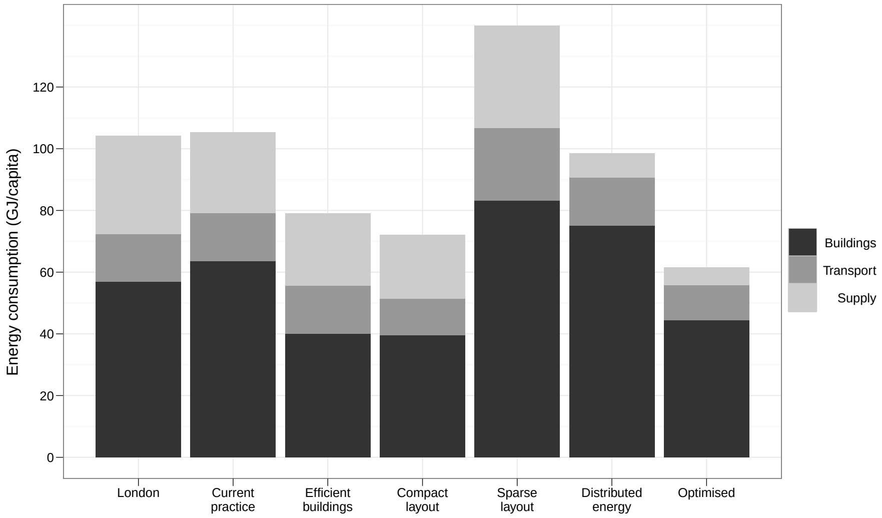
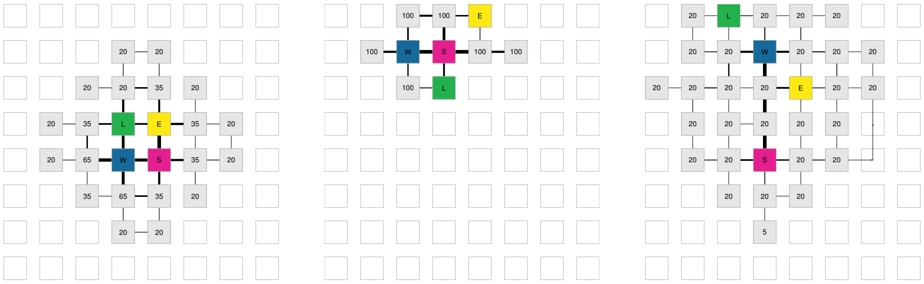


Figure 8: Energy consumption in each scenario by sector. The "supply" category represents the required primary energy inputs.

In the discussion below, energy and carbon savings are measured relative to the known London baseline. Energy system costs are compared with the estimated "current practice" scenario.

Quality of the built environment Improving the energy performance of the built environment achieves significant savings. Compared to the London reference case, total primary energy consumption and carbon emissions fall by 24% and 27% respectively as heating requirements are reduced through the improved insulation and air-tightness of the SAP 100 rating. Relative to the "current practice" estimate of costs, the resulting energy system is 29% cheaper primarily through fuel savings. Note however that the energy system costs do not include the increased costs of building to this standard: only the costs of conversion equipment (e.g. domestic gas boilers) and imported fuels are counted.

Urban form The density of the urban form also shows expected trends. First, in the compact layout case, the increased density means that individual dwellings are smaller and with less external wall area per dwelling, heating demands are reduced resulting in primary energy savings of 31% and carbon savings of 33%. Conversely, in the sparse layout case, the construction of large houses in a low-density sparse layout increases these heat losses, leading to primary energy and carbon increases of 34% and 27% respectively. The differences are also partly explained by the transportation sector, which sees energy savings of 24% in the compact case and increases of 51% in the sparse layout. The layouts for these different scenarios are shown in Figure 9.

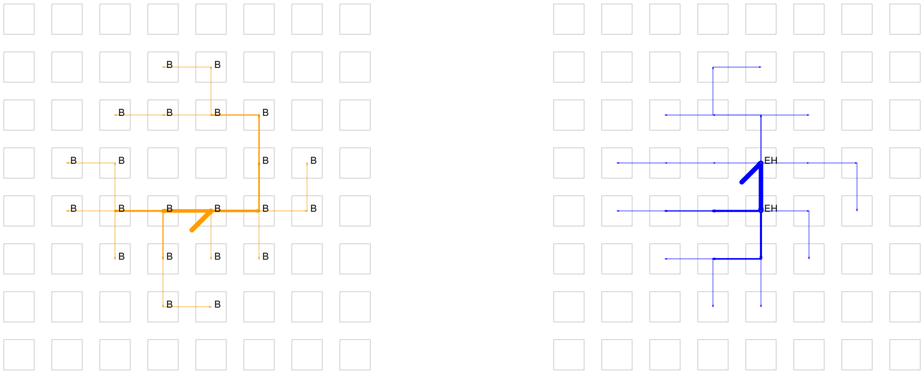


(a) Current practice (b) Compact (c) Sparse

Figure 9: Urban layouts, from (a) to (c): the assumed mononuclear city, a compact city with high density housing, a sparse city with low density housing. In each figure, the coloured cells represent activity provision: green for leisure (L), blue for work (W), pink for shopping (S), and yellow for education (E). The pale grey cells represent housing with the labels indicating the density in dwellings per hectare. The black lines connecting the cells indicate road connections and indicative traffic flows.

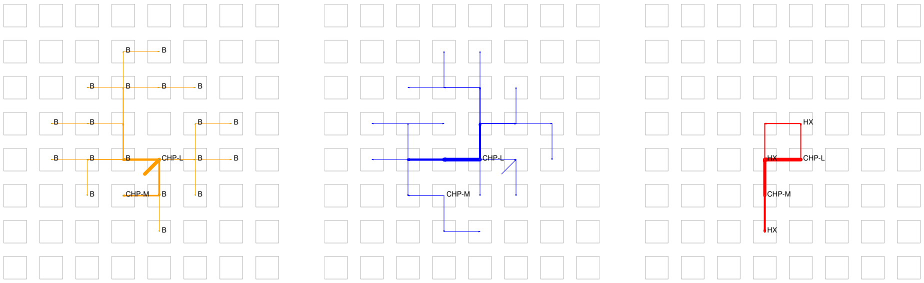
Energy system When combined with a standard density layout, the switch to a district energy system appears to deliver small primary energy and carbon savings (5% and 13% respectively). The system however is an important part of the overall optimised scenario, which has a notably higher heat load density. The district energy system case is also noteworthy as it illustrates the importance of comparing the scenarios on a primary, not final, energy consumption basis. From a final energy consumption perspective, the district energy system appears to be worse, leading to a 25% increase in energy consumption. However this is simply because the inefficiencies of producing electricity from gas have been imported within the city boundary.

The structure of the energy systems is shown below. Figure 10 illustrates the current practice case, wherein heat demands are met by small gas boilers and electric heaters. In contrast, Figure 11 features a small district heating system powered by two 6 $\mathrm{MW_{thermal}}$ and one 3 $\mathrm{MW_{thermal}}$ gas-fired combined heat and power units. The imported flow of electricity is much lower here.



(a) Gas network (b) Electricity network

Figure 10: Resource distribution networks for the current practice scenario. Resources are imported to the centre of the city (diagonal arrows) and distributed to the end demands. Heat demands are met by gas boilers (B) and electric heaters (EH, used only during peak demand).



(a) Gas network (b) Electricity network (c) Heat network

Figure 11: Resource distribution networks for the distributed energy scenario. Imported grid gas and electricity are again shown by diagonal arrows near the centre of the city. Two 6 MW (CHP-L) and one 3 MW (CHP-M) district CHP units are located nearby. These convert gas to heat and electricity, distributing these outputs to nearby cells; heat exchangers (HX) are then used to convert this higher grade district heat into domestic space and water heating. Boilers (B) provide heating in areas of lower demand.

Costs

Figure 12 summarizes the costs of each solution broken into capital and fuel costs. In all of the scenarios, fuel costs dominate the capital costs but the capital costs are much larger for the distributed energy and optimised solutions, which include CHP plants and district heat networks. As the costs represent annualised values, this mix will of course vary based on the financing terms for the capital equipment (assumed here to be 6% over 25 years).

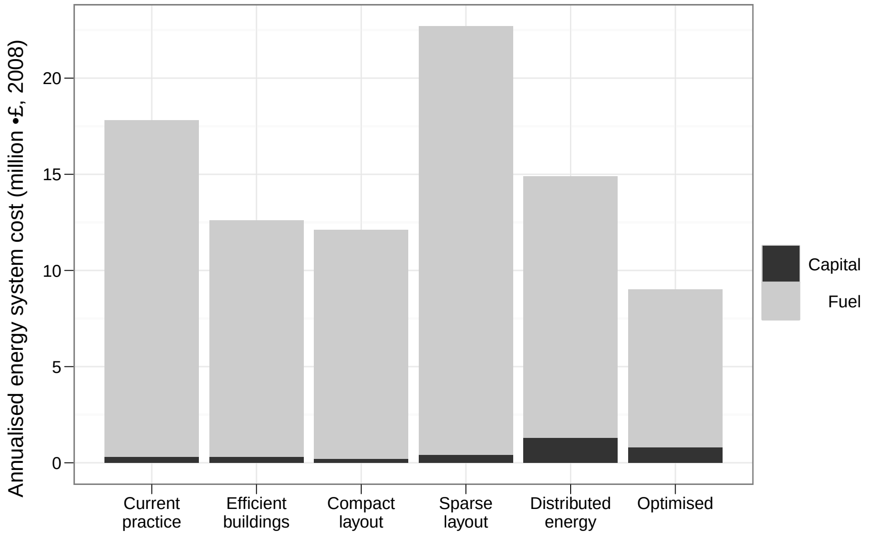


Figure 12: Energy system costs under different scenarios.

While the precise balance of costs may vary depending on one's assumptions, it is important to note that the costs cover the entire energy system, regardless of who pays. For example in the (UK) "current practice" scenario, the cost of installing the gas and electricity networks would be covered by the utilities with the boilers and fuel costs being met by households. However in the distributed energy and optimised scenarios, almost all of the costs are borne by the utility as they now pay the fuel and capital costs of installing and running large CHP units. These cost structures must therefore be carefully considered by policy makers if the most efficient – both in terms of overall system costs (i.e. societal costs) and energy performance – solutions are to be achieved.

Summary

The results indicate that the combined effect of each intervention cannot be summarised using an additive "wedge" model. There are interactions between effects of density, built fabric quality and energy system design. Policy packages that address only one of these improvements may therefore miss important opportunities for positive interaction effects and further savings. For example, more efficient building fabrics can reduce the heat demands of individual dwellings but, without high development densities, overall building demands cannot be serviced by higher efficiency district energy systems which require spatially-concentrated heat demands. The modelling results presented here suggest that when all three improvements are combined – higher density, improved built fabric, and an efficient energy supply system – significant savings are possible: 41% in primary energy consumption, 45% in carbon emissions, and 49% in system costs.

6 Discussion and conclusion

This paper has utilised an integrated modelling system known as SynCity to examine several key questions surrounding urban energy systems. This section briefly summarises the results and considers their implication for policy makers and modellers.

6.1 Summary of results

In the first two analyses, specific aspects of urban energy consumption were addressed. Considering the layout of an urban area and its density, a Monte Carlo analysis showed that, for every additional 1% of total housing allowed to come from high-density forms (65 dwellings/hectare), 0.35% of total final energy consumption is saved (relative to a 10% high-density baseline). Developers and planners can use this information to determine how best to compromise between efficient urban layouts and the heterogeneity of form they may wish to maintain for aesthetic or functional reasons.

For a given layout and pattern of demands, a variety of energy systems can then be used. Using the resource-technology network model, it was shown that the most efficient scenarios, balancing both cost and energy performance, require a mix of technologies appropriately sized for the city's demand. In particular, the study suggested that restrictions on the maximum size of combined heat and power units, either through planning concerns or lack of available space and infrastructure, can result in system cost increases of 10% and energy consumption increases of 43%.

Finally the entire SynCity system was used to evaluate the effects of urban density, energy systems design, and the quality of the built environment, both as stand-alone interventions and as part of an integrated policy package. The results showed that improving the built fabric and using more compact forms each result in primary energy savings of 25 to 30% relative to a "current practice" base line. However the benefits of district energy systems are most notable when combined with high-density forms and efficient buildings, leading to an overall minimum energy scenario which saves 41% primary energy and 49% costs relative to the baseline.

6.2 Policy implications

The model presented here is one approach to informing policy debates about efficient urban energy systems. Detailed studies will be important to understand the precise measures that should be taken for any single city, as differences in geography, economics and politics all shape the feasible space for efficient solutions. Nevertheless a few general conclusions can be drawn from the current study:

- Final energy consumption is not a sufficient indicator of energy system performance. In cogeneration systems in particular, this metric may show an increase in delivered fuel consumption which masks upstream conversion and distribution losses. Primary energy consumption should therefore be the basis of scenario comparisons.

- The precise value and mix of total annual energy system costs, i.e. the fuel and capital equipment costs, will depend largely on the financing terms one assumes. However the analyses showed that the burden of these costs will vary significant depending primarily on the energy system configuration. In current (UK) practice, most of the capital and fuel costs will be paid by end consumers whereas in a distributed energy system, much more of the costs will be borne by energy utilities. This suggests that in order to achieve overall system efficiency, policy makers should design markets that help utilities to implement distributed energy installations despite their unique capital and fuel cost structures.

- The integrated analysis showed that density is a key parameter, both on its own and in combination with other factors. Higher densities imply smaller dwellings with lower energy demands, shorten transport distances and enable district energy systems. More generally, all three case studies indicate the importance of urban planning measures. These decisions – for example, on building energy performance standards or the location of infrastructure – are difficult to change in retrofit and can lead to significant increases in energy consumption; in the cases studied here, urban sprawl led to a one-third increase in primary energy consumption. Efficient distributed energy systems can, to a certain extent, can be retrofitted into existing urban forms but they too can benefit from long-sighted urban planning by encouraging sufficient demand density and by reducing the costs of network infrastructure. Regulations concerning the presence of large energy plants within the urban form are also a key part of a forward-thinking urban energy planning environment.

6.3 Methodology improvements

The development of SynCity is continuing, with a focus on both new case studies and improvements to each component model. A particular area of interest is the modelling of agent-activities and the resulting demands for transport energy. Transport was considered briefly in the current analysis but a more detailed assessment, looking at mode choices and network routing, would be valuable. Improved modelling of agent behaviour also enables in-home energy use to be studied in greater detail and facilitates assessments of price-based policy interventions.

Acknowledgments

The financial support of BP via the Urban Energy Systems project at Imperial College London is gratefully acknowledged.

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