SYNCITY: AN INTEGRATED TOOL KIT FOR URBAN ENERGY SYSTEMS MODELLING

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ABSTRACT
This paper demonstrates a new tool for the integrated modelling of urban energy systems. Energy is vital to the delivery of urban services and its role can be considered at many stages in the urban design process. This begins with the planning and layout of a new city, through to the socio-economic structure of the city and its activities, and the choice of energy carriers and technologies used to meet these demands. Unfortunately existing modelling technologies typically focus on only one of these components and are customised to a single problem context. We have therefore developed a “synthetic city” tool kit (SynCity) to facilitate the integrated modelling of urban energy systems across all of these design steps and in a variety of problem environments. After outlining the components of this methodology, we demonstrate how it can be applied to the case of a UK eco-town. The discussion then considers the wider applicability of the SynCity methodology and highlights potential use cases.

KEYWORDS
Integrated modelling; optimisation; eco-towns
I. INTRODUCTION

In recent years there has been a surge of interest in urban climate and energy issues. These trends can be encapsulated by two notable reports. First, the UN’s most recent population estimates show that over 50% of the world’s population now lives in urban areas, a number that is expected to continue rising particularly in developing nations (UN 2008). Secondly, last year’s World Energy Outlook (IEA 2008) explicitly focused on urban energy use, noting that approximately 2/3 of world primary energy is consumed by cities and again forecasting continued growth in both developed and developing countries. These facts – combined with the activities of organizations such as the Global Carbon Project’s Urban and Regional Carbon Management theme, ICLEI’s Cities for Climate Protection, the C40 Climate Leadership Group, Energie-Cités, Columbia University’s Urban Climate Change Research Network and many others – reflect a growing recognition that energy use in cities is a key element in the fight against global climate change.

Unfortunately the scale of the challenge seems only to grow larger. In March 2009, the International Scientific Congress on Climate Change in Copenhagen observed that “given high rates of observed emissions, the worst-case IPCC scenario trajectories (or even worse) are being realised”, therefore increasing the likelihood of “abrupt or irreversible climatic shifts” and associated social and economic disruptions (ISCCC 2009). Furthermore, the global economic downturn has restricted credit for new innovations, created a more risk-averse investment climate and strained public sector finances. With scarce resources and the need to achieve greater carbon savings, improvements to urban energy systems will increasingly require integrated solutions that deliver maximum economic efficiency and multiple benefits.

Yet before cities commit to significant new policy initiatives or infrastructure investments, there is a need to improve our understanding of urban energy use and how it might be changed. Typically this would typically be a job for mathematical modelling or computer simulations; while such models can never provide a definitive answer to policy makers (because modelling technologies are always partially incomplete and policy debates need to consider other forms of knowledge alongside numerical analyses), they are an important contribution to urban sustainability debates (Tweed and Jones 2000).

Urban modelling technologies have been developed to cover a range of applications, but they are most commonly found in the area of land use and activity location. Batty (2007) notes three major model classes: land use and transportation models (e.g. CUSPA 2009), urban dynamics models (i.e. aggregate system dynamics), and micro-simulation models (e.g. cellular automata and agent-based models). These tools focus primarily on economic or spatial planning issues, but some groups have adapted these technologies to perform climate risk or environmental modelling; a notable example is the Tyndall’s Centre integrated assessment model which is currently being applied to the climate risks of London’s spatial plan (Dawson, Hall, Barr, et al. 2009).
There have also been efforts to develop tools for urban energy systems modelling. These include: a tool for the assessment of energy, water and waste consumption at a building or small neighbourhood level (Robinson, Campbell, Gaiser, et al. 2007), a GIS tool for estimating the spatial pattern of energy requirements in an urban area (Girardin, Dubuis, Darbellay, et al. 2008), a model assessing the interactions of heat demand and locally available heat sources, e.g. lakes or incinerators (Mori, Kikegawa and Uchida 2007) and a model combining demand estimation with an energy-management optimisation module (Brownsword, Fleming, Powell, et al. 2005). While these applications are quite diverse, they demonstrate two important features of existing urban energy system models. First, such models must include a representation of the spatial and temporal variation of urban energy demand. This can lead to significant input requirements, e.g. in the form of GIS data or building design information specifications, but building up the urban system from individual components allows the aggregate effects of small changes to be assessed more readily. Second, these models seek to explore both the supply and demand sides of urban energy use, for example by optimising provision strategies. However in addition to these positive characteristics, these examples also show that current practice consists largely of detailed models built for the assessment of a single aspect of existing systems (e.g. domestic sector demands in UK households, heat demand in Geneva, etc.). This means that these tools have limited applicability beyond the specific problem case, increasing the resources required for data collection and validation in new contexts. Furthermore they are unable to offer a truly integrated perspective on urban energy use across all sectors and stages of the design process.

The goal of our paper is to demonstrate an improved technique for the modelling of urban energy systems. This “synthetic city” approach (SynCity) seeks to provide an integrated, spatially and temporally diverse representation of urban energy use but within a generalised framework. By dividing urban energy use into a series of separate but integrated models and through the use of mathematical modelling techniques, rather than detailed data sets, we believe that the SynCity system can be applied in a variety of problem contexts. After giving a detailed overview of the system, we apply SynCity to the case of a UK eco-town to demonstrate each major component. In the concluding discussion, we consider the potential use cases of the tool kit with reference to the goals of this symposium.

II. OVERVIEW OF THE SYNCITY TOOL KIT
The SynCity tool kit is the main activity of the BP Urban Energy Systems project at Imperial College London. This interdisciplinary project began in 2005 and it seeks to “identify the benefits of a systematic, integrated approach to the design and operation of urban energy systems, with a view to at least halving the energy intensity of cities” (Shah, Fisk, Davies, et al. 2006). To achieve this goal, the project employs researchers with a range of expertise including process systems optimization, urban and industrial ecology, transport and land use modelling, energy systems modelling, energy policy and business strategy.

After reviewing the relevant literature in these fields, the team began to develop SynCity as an integrative test bed for research activities. It was envisioned that
the software would enable each team member to perform analyses specific to their field of interest, while transparently drawing on the contributions of other team members. The goal was therefore to have a system that did not require excessive data collection or parameterisation for each model run and could simulate a variety of urban energy modelling problems. It was in this context that the structure of the SynCity system was developed.

1. SynCity structure

The SynCity tool kit consists of three major components: a series of models designed to handle specific urban energy design problems, a unifying ontology and database to describe and store core data objects, and an executive to assemble and coordinate the running of modelling scenarios. These relationships are depicted in Figure 1.

![Figure 1. Overview of the SynCity tool kit](image)

Briefly, the ontology provides a description of the major objects within an urban energy system. The idea is that this data model can be consistently referenced by both software objects and team members to promote a common understanding of complex concepts. For example, a transport modeller and an electricity system modeller would both share a common view of a network as a mathematical graph, but they might also require additional information about the properties of edges and nodes (e.g. electrical resistance, maximum number of vehicles per hour). Five major object categories were identified: *resources*, i.e. materials that
are consumed, produced or inter-converted including gas, electricity, and so on; processes, i.e. technologies that convert one set of resources into another set (e.g. a gas turbine that converts gas to electricity and waste heat); technologies, i.e. the infrastructure of a city including buildings and networks; spaces, i.e. the physical space of the city and its surrounding hinterlands; and agents, i.e. the occupants of the city including citizens, firms, and government actors. These concepts were then codified into an ontology using Protégé (Noy and McGuinness 2002) and converted into a MySQL database model and relevant Java classes.

The SynCity executive is a Java API (application programming interface) that enables users to manipulate these core data objects and assemble them into modelling scenarios. The API consists of three major object class types: data classes (as described above), model classes (for implementing the sub-models, either directly in Java or via other software packages), and manager or utility classes, which handle file management, model execution and so on. As there is currently no graphic user interface for SynCity, users build their simulations with Java code using this API. Pseudo-code for a typical model application is shown in the appendix.

2. Sub-models
The heart of the SynCity tool kit contains three sub-models, each designed to handle a specific part of the overall urban energy system analysis. The models are designed to be run sequentially, but the system is modular and steps can be skipped if not required. Similarly there are plans to allow the models to feedback within the system, thus facilitating iterative design processes.

2.1 Layout model
The first component is a layout model which seeks to optimise the design of the city based on minimising cost, carbon or energy consumption. The inspiration for the model comes from flow-based factory design models and optimised urban layout sketches (e.g. Feng and Lin 1999, Urban, Chiang and Russell 2000). As input, the model takes the geography of the city, the available types of residential and commercial buildings, available transportation infrastructures and modes, and average activity profiles of the citizens. Using mixed-integer linear programming (MILP) techniques, the model then seeks to position buildings, activity locations, and transport networks subject to basic constraints. For example, there must be sufficient housing for the entire population, each activity can only provided in certain types of building and buildings can only be constructed on suitable land types.

The model is typically run for green-field sites and therefore has significant freedom in deciding where to locate buildings and networks. However users can add additional constraints, e.g. by fixing the location of certain facilities in advance, in order to simulate brown-field developments and to represent the connections between the proposed development and existing neighbouring settlements.

2.2 Agent activity model
The agent activity model is an agent-based micro-simulation model. Beginning with the layout of the city (either manually specified or calculated by the layout
model), the model simulates the daily activities of each citizen within the city. This is currently implemented as a simple four-stage transport model: that is, in each time step of the model, citizens select an activity (trip generation), an activity provider (trip distribution), a transport mode (mode choice) and a route (trip assignment). Each of these decisions is stochastic; for example, the trip distribution step uses a gravity-model to assess the attractiveness of alternative service providers. This variability, combined with the interactions between agents (e.g. congestion of a network path), allows the agent activity to capture some of the complex emergent properties of urban systems.

As the agents within the model perform their daily schedules, demands are created for resources such as electricity, heat, or transport fuel; similarly resource supplies can be created by agent activities (such as waste) or they can occur naturally (such as ground-source heat). These supplies and demands are distributed in time and space, providing the primary input for the next model stage.

2.3 Resource-technology network model

The resource-technology network (RTN) model is an optimisation model which seeks to design the overall energy-supply strategy for the city. It takes as input the spatially and temporally distributed resource demands determined by the agent-activity model, as well as sets of available process types. These processes describe how resources can be produced (e.g. converting from gas to electricity), transported (to accommodate spatial variance in demand) or stored (to accommodate temporal variance in demand). The model enforces a resource balance in every cell to ensure that all resource demands are satisfied using the outputs of these three process types, and the ability to import or export resources to and from the surrounding hinterlands. The objective function currently minimizes the cost of providing the entire energy supply system (i.e. generating equipment, transportation networks, resource imports) and consequently the model can evaluate, for example, the tradeoffs between an electricity generation system with gas distribution and household boilers for heat provision, or a district heating system that uses a heat network to move excess process heat from source to demand. The output of the model is a map giving the location of each conversion process and the structure of the resource distribution networks, as well as details of the rates of resource import, export, production and consumption at each time step.

It should be noted that a fourth sub-model component, the service network model, is currently in development. This will convert the macro-scale network designs produced by the RTN model into a more detailed engineering specification.

3. Data requirements

As noted above, one of the goals of the SynCity tool kit is to create a model that can be transferred between different problems with minimum additional data collection. At present the system is backed by a database of approximately 30 resources, processes, and technologies whose parameters are generally transferable, although the cost data associated with each object is likely to change between locations. Consequently, we have found that a new case study
can be quickly run using the information commonly available on a site master plan (e.g. spatial layout, population, housing densities); this provides an initial result that can then be refined later in consultation with the client.

III. APPLYING SYNCITY TO A UK ECO-TOWN

A number of potential use cases for the SynCity tool kit have been identified. These include developing the layout of a new development, assessing centralised and decentralised energy provision strategies for a city, and evaluating the potential of refurbishment programs for an existing city. Here, we demonstrate the SynCity platform using a proposed UK eco-town, as it touches on each component of the tool kit.

1. Introduction to the case

Given rising demand for housing as well as substantial questions about how the building sector might contribute to national climate change and energy policy goals, the UK government has promoted “eco-towns” as an opportunity to drive innovation and to demonstrate how these policy goals might be jointly achieved. While the formal requirements for eco-town certification have not yet been announced by the government, it has been suggested that the headline targets for these developments should be an 80% reduction in CO₂ emissions (versus 1990 levels) and an ecological footprint two-thirds of the national average (CABE and BioRegional 2008). Twelve eco-town developments have been put forward for consideration and this paper considers one of these proposals.

The site is located in central England and our analysis has focused on one of the design phases, an area of approximately 90 hectares intended to house 6500 people. An initial assessment of the proposal by government-commissioned consultants found that the site “might be a suitable location subject to meeting specific planning and design objectives” (DCLG 2008), but more information was required particularly on the energy strategy for the site. Since then, a study of alternative energy systems has been commissioned by the developers to address some of these criticisms. However the fate of this and other eco-town proposals is uncertain given the current economic climate and the falling UK housing market.

The present analysis was designed to assess the performance SynCity platform across each of the three modelling components. The research questions are therefore:

- How do the designs created by the layout optimisation model compare with the proposed eco-town master plan?
- Does the current agent-activity model provide a reasonable estimation of energy demands, when compared with the design assumptions of the eco-town developer’s energy strategy?
- How does the RTN model respond to changing assumptions about the provision of energy services for the eco-town?
2. Layout model results

The developers of the proposed eco-town have already created a master plan for the site and we were asked to use SynCity to assess this design and explore alternative layouts. The layout model can provide an initial evaluation of such designs by calculating the estimated annual cost (capital and operating), energy and carbon emissions for buildings and anticipated transportation flows.

We began by converting the geography of the site from a GIS shape file to a simple cellular representation, maintaining the area and relative separation of each cell. Using the master plan, the location of known housing and activity types were fixed before allowing the layout model to estimate the associated transportation flows as shown in Figure 2. This provides a baseline result for comparing alternative designs. (Due to commercial confidentiality concerns, it was difficult to get accurate cost data for each building and infrastructure type; the results therefore compare costs as normalized against this modelled baseline).

Figure 2. Layout of the eco-town as planned

In these plots, each cell is coloured according to the building type located on the cell; for example, schools are yellow, parks are green, and housing is blue (with darker shades representing higher dwelling densities). The activity performed at each cell is indicated by the label and the width of the connecting lines represents the traffic flows between each cell. In all cases, a list of possible network connections is given as input to the model in order to prevent the connection of non-neighbouring or otherwise separated cells. Single nodes are also used to collect transport demand from local cells to a specific point, an approach commonly used in transport modelling.
After establishing the baseline master plan layout, the model was run in an “unconstrained” mode: that is, the model sought to provide sufficient housing and activities for the estimated population but with no additional constraints on how these demands were met. The result, shown in Figure 3, demonstrates that the optimiser found a solution that relied heavily on high-density housing as this provides accommodation in the most cost-effective manner. Similarly, the amount of open space provided was limited and clusters of housing and activities can be seen gathered around each transport node (minimizing transport costs).

![Figure 3. Cost-optimised eco-town layout (unconstrained)](image)

After discussing this layout with the developers, it was clear that such an extreme optimisation would be undesirable in practice. For example, planning restrictions require a minimum total area of open space per capita and the exclusive use of high-density housing would mean that the eco-town might not be a suitably attractive place to live. A second optimisation was therefore run after adding corrective constraints on the maximum total area for high-density housing and parkland and the minimum and maximum lot areas for mixed use and school facilities. The solution in Figure 4 shows a layout that is remarkably similar to the original master plan, although the housing density is still somewhat higher and some cells are unused.
The three scenarios are summarised in Table 1. The results suggest that, when compared to the reference master plan case, an optimised layout could deliver up to a 60% reduction in total development costs, and an approximately 80% reduction in energy consumption and carbon emissions. Even when constraints are added to reflect the more realistic conditions of planning regulations and commercial viability, significant savings of approximately 40% are seen.

Table 1. Comparison of layout model scenarios

<table>
<thead>
<tr>
<th></th>
<th>Master plan</th>
<th>Unconstrained</th>
<th>Constrained</th>
</tr>
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<tbody>
<tr>
<td>High-density housing (% of total housing area)</td>
<td>0</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>Total housing provided (people)</td>
<td>8297</td>
<td>6576</td>
<td>6760</td>
</tr>
<tr>
<td>Average daily travel (pass-km)</td>
<td>10400</td>
<td>6240</td>
<td>9220</td>
</tr>
<tr>
<td>Network length (km)</td>
<td>19.9</td>
<td>14.7</td>
<td>17.4</td>
</tr>
<tr>
<td>Relative annual cost (Master plan = 100)</td>
<td>100</td>
<td>41</td>
<td>64</td>
</tr>
<tr>
<td>Annual energy consumption (GJ per capita)</td>
<td>86.2</td>
<td>19.3</td>
<td>52.3</td>
</tr>
<tr>
<td>Annual carbon emissions (tC per capita)</td>
<td>2.56</td>
<td>0.54</td>
<td>1.53</td>
</tr>
</tbody>
</table>
The layout model can also incorporate the provision of activities in “hinterlands” (e.g. neighbouring cities) and optimise for other goals (such as minimum carbon or energy consumption). However due to space constraints, such results are not presented here.

3. Agent-activity model results

A fully-detailed agent-activity model is currently under development but this study was conducted using a less complicated version which requires very little computational overhead but must be tested to ensure that it generates realistic resource demands. (This demonstrates the advantage of SynCity’s modular approach: once the full version of the agent-activity model is complete, it can directly replace the current simplified version with no additional effort because the inputs and outputs are identical.) Using the constrained layout calculated above, the agent-activity model was therefore run to compare the calculated demands against those values estimated by the developers.

The model begins by assigning the population to houses and employers within the city layout. Time within the model is divided into 16 periods representing 4 times per day, 2 types of day (weekday, weekend), and 2 seasons (summer, winter). Each time period has different profiles for the types of activities that citizens might like to perform (e.g. higher propensity for work during weekday daytime) and depending on their unique characteristics (e.g. age, education, income), a unique schedule of activities is chosen for each citizen. These activities are then performed and the associated demands for travel, heat, electricity and other resources are calculated.

Table 2 summarises the results of the model. The total demands for heat and electricity are very close to the reference values, although there is insufficient data available to ensure that the spatial and temporal distributions match. The daily trips generated by the agent-activity model are also similar to the reference case. However there is insufficient data to verify the modal distribution; the agent-activity model estimates that bus travel accounts for 94% of motorised trips, which likely underestimates the use of private cars. As a result the demand for transport fuel calculated by the model (~20 L per person per year) was deemed to be unrealistic and the subsequent RTN analysis therefore focuses only on the provision of heat and electricity.

Table 2. Comparison of SynCity agent-activity model results to eco-town reference

<table>
<thead>
<tr>
<th></th>
<th>SynCity</th>
<th>Eco-town reference</th>
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<tbody>
<tr>
<td>Annual heat demand</td>
<td>5100</td>
<td>5200</td>
</tr>
<tr>
<td>(kWh per capita)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual electricity</td>
<td>2500</td>
<td>2080</td>
</tr>
<tr>
<td>demand (kWh per capita)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily motorised trips</td>
<td>0.48</td>
<td>0.45</td>
</tr>
<tr>
<td>(per household)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4. RTN results

The resource-technology network (RTN) model is designed to select an optimal (in this case, lowest cost) energy-supply strategy for a pattern of resource demands. Four different supply strategies are available to meet a resource demand: importing the resource from a hinterland, receiving transfers of the resource from another location within the city, creating the resource locally (e.g. by converting other resources), and retrieving stored resources.

Two simple cases are considered here. First, we assume that for a small development of 6500 people, the business-as-usual case would involve importing all of the required resources from external hinterlands: in other words, importing gas and electricity from national grids. Small household-scale technologies (such as 20 kW boilers) are then used to convert the gas into the required heat demands. The model is constrained to import resources to only one cell per resource and a network configuration is then calculated to distribute these resources to their demand locations. Figure 5 overleaf shows the resulting layout for the gas and electricity networks.

In the second case, we note that the developers expressed interest in providing district heating at the site. We therefore restrict the model, forbidding it from importing electricity but allowing it to install a 50 MW combined-cycle gas turbine (CCGT) somewhere within the city, with an associated district heat network. Figure 6 shows the resulting networks for gas, electricity and district heat. District heat is clearly provided only to those heat demands near the CCGT unit (using a heat exchanger to convert district heat to domestic grade heat), with gas being transported by pipeline to other locations and converted to heat in domestic boilers. Electricity is provided entirely by the CCGT and distributed to the points of demand.

In each plot, the grey boxes represent a location within the city although not all cells have resource demands. Resource flows are shown by the arrows: bold vertical lines represent imports and the width of the line is proportional to the resource flow. Labelled circles within a cell represent the presence of one or more conversion technologies (“heatex” = heat exchanger, “boilers” = household-scale gas boiler, “ccgt_heat” = combined-cycle gas turbine with district heat take-off).
Figure 5. Distribution networks and conversion technologies for gas (top) and electricity (bottom) in the import-only scenario.
SynCity: a tool kit for UES modelling
IV. DISCUSSION AND CONCLUSION

These examples have briefly demonstrated the capabilities of the SynCity tool kit, a three-stage system for the modelling of urban energy systems. In the first layout step, it was shown how a mixed-integer linear programming model can be used to develop alternative master plans for a new development with up to 80% reductions in cost and emissions against a business-as-usual scenario. With the addition of a few basic constraints, the design can be modified to reflect the requirements of a realistic developer while still delivering significant efficiency gains. Second, an agent-activity model was used to determine how individual agents might interact with this urban infrastructure creating a spatially and temporally varied pattern of resource demand. While a more elaborate version of this model is currently being developed, the results calculated here are very similar to those assumed by the developer, indicating that the current model is a good placeholder implementation. Finally, a second optimisation model was used to determine how these patterns of resource demand can be satisfied most cost-effectively using a combination of local conversion technologies and imported resources. The import-only and constrained-import examples demonstrate how the model framework can be easily adapted to assess alternative energy supply strategies.

The case studied here represented a proposed eco-town development in the United Kingdom but the design of the SynCity system is intended to be flexible so as to be applicable to other contexts without extensive customization. Indeed in another case study, we were able to perform an initial assessment of a Chinese development in approximately two days using data available from the project master plan. However, while our general development strategy is to ensure that the tool kit remains as broadly applicable as possible, the inclusion of specific features is driven by a set of hypothesised use cases. These include:
• **Brownfield developments**: By fixing some components of the layout model, existing land uses can be represented and re-development strategies for small intra-urban land areas explored.

• **Retrofit assessments**: A new version of the RTN model is currently in development that will allow an investment budget to be used for supply provision, demand management, or a mix of both. This will enable the model to compare retrofit programmes, such as insulation drives, with the cost of providing additional energy supplies.

• **Developing-country assessments**: The SynCity system is supported by a database of technologies and resources, which can be extended or modified as necessary for different countries. In particular, cost data within the model currently draws on UK assumptions; while some products may be purchased in international markets at comparable prices, these data are not fixed and costs can be changed to reflect local conditions. Applying SynCity in wider contexts, especially in developing countries, will help us to identify these location-specific factors and improve the methodology.

• **Themed-city assessments**: The RTN model is built upon a highly abstracted view of energy resources and technologies and it can be restricted to consider only certain resources and conversion technologies. This facilitates the analysis of “themed cities”. For example, in a developed country, this may mean the provision of biomass-fired district heating or a hydrogen city; in developing countries, technologies such as open fireplaces or kerosene burners could be simulated. Both examples only require changes to the model’s input data.

• **Impact assessments**: The RTN model enforces a strict resource balance meaning that the outputs of fuel consumption must be explicitly accounted for. While waste heat is currently the primary waste output (e.g. for assessing heat island impacts), other wastes (e.g. tCO$_2$e, NOx, PM$_{10}$) can be included as additional resources that are generated by certain processes or agents’ activities. Work is also currently underway to incorporate a full spectrum of global warming potential, resource depletion and local air pollution indicators in a more efficient manner.

• **Dynamic assessments**: Although the models currently consider dynamic resource supplies and demands, the proposed layouts and technologies are all assumed to be static. However using multi-period optimisation techniques, we hope to facilitate assessments of phased energy infrastructure investments, as well as detailed agent behaviour models to simulate the impact of policies over different time scales (e.g. congestion pricing in transport on a daily scale, through to market transformation policies over a multi-year period).
These cases reflect the wide range of urban energy issues currently facing policymakers, engineers and other stakeholders. Although still in a prototype stage, we believe the SynCity tool kit offers a powerful platform for the integrated modelling of urban energy systems. While other systems will still be required for micro-assessments, the capabilities presented here show that SynCity uniquely allows users to evaluate holistic urban energy strategies from the early master plan stage through to the assessing the impacts of a specific energy supply strategy. Development of the platform continues, with a view to providing a stable tool kit to users in both the developed and developing world.

V. ACKNOWLEDGEMENTS

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

VI. REFERENCES


VII. APPENDIX

The SynCity tool kit is built using the Java programming language. Listing 1 provides a pseudo-code demonstration of a typical model run, illustrating the system’s three key features: an urban energy object database, three component sub-models, and an overall scheduling executive.

```java
// connect to database and other initialization
init();

// Create an empty city
City c = new City();

// Load relevant data objects from database
c.addResource("elec");
c.addProcess("ccgt");
...

// Create a manager to handle simulation and store results
Manager m = new Manager("d:/output/");

// Assign city to manager
m.setCity(c);

// Create submodels
Model layout = new LayoutModel();
Model abm = new TransportABM();
Model rtn = new RTNModel();

// Add models to manager
m.addModels(layout, abm, rtn);

// Execute models
m.executeModels();
```

Listing 1. Pseudo-code of typical SynCity model

VIII. LIST OF ACRONYMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>API</td>
<td>application programming interface</td>
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<tr>
<td>CCGT</td>
<td>combined-cycle gas turbine</td>
</tr>
<tr>
<td>GIS</td>
<td>geographic information system</td>
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<tr>
<td>ICLEI</td>
<td>International Council for Local Environmental Initiatives</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<tr>
<td>MILP</td>
<td>mixed-integer linear programming</td>
</tr>
<tr>
<td>RTN</td>
<td>resource-technology network</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
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<tr>
<td>UN</td>
<td>United Nations</td>
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