bp-Imperial College Urban Energy Systems Project

Sixth Annual Report (2011-12)

Dec 2012

Contents

1. Executive Summary

The BP Urban Energy Systems project at Imperial was set up to identify the benefits of a systematic, integrated approach to the design and operation of urban energy systems, with a view to identify large reductions in the energy intensity of cities. The major outcome from the programme has been the development and validation of the SynCity toolkit for modelling energy use in cities in an integrated way. It provides a significant step forward in modelling and evaluating city energy use in a comprehensive and coherent way. The project has also helped develop an agent based micro-simulation modelling framework for generating demand forecasts based on individual activities and behaviours.

The project was predicated on the assumption that while individual urban energy systems may have been optimised there has been no attempt to cross-optimise over cities' total energy consumption. Such system wide optimisation has improved efficiency by several tens of percent in other systems such as refineries and petrochemical complexes. The research challenge is that cities are more than an order of magnitude more complex, involve diverse energy vectors and are confounded by the daily decisions of millions of individuals (agents) and so a new modelling framework is required. The SynCity framework successfully meets this challenge.

The first year's programme aimed at assessing the state of the art in urban energy systems modelling and related disciplines, while the second year focussed on developing our own modelling framework. The third, fourth and fifth years have involved refining and extending our modelling framework, developing an urban energy systems modelling and design tool and performing validation studies.

This final year has focussed on finalising the programme and packaging the outputs effectively. Major achievements include:

- Contributions to a chapter of the Global Energy Assessment: (http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/Home-GEA.en.html)
- Contribution to an associated book: Energizing Sustainable Cities: Assessing Urban Energy (Eds: A Grübler and D Fisk).
- The completion of our own book: Urban Energy Systems (Eds: J Keirstead and N Shah)
- The continued development and demonstration of a hierarchical modelling framework (SynCity) for urban energy systems based on four interacting layered models: the urban layout model, the urban agent-based transport-land use (ABMS) model, the urban resource-technology network (RTN) optimisation model and the energy service network model
- The enhancement of the SynCity tool, in particular developments in:
    - Development of a next generation ABMS – with a higher temporal resolution and more sophisticated agent behaviour including information on technology holdings
    - A new user graphical interface targetting the non-expert user
    - An improved RTN model with better peak-average modelling and preliminary multiperiod modelling capability

The remainder of this report is organised as follows:

- Section 2 describes in more detail the project background, objectives, programme and organisation
- Section 3 presents the SynCity toolkit and relevant major developments
- Section 4 describes the SynCity component models
- Section 5 presents some highlights of the year
- Section 6 outlines the Consumers and Business workstreams
- Section 7 explains the collaboration strategy for the project and lists the key collaborative activities
- Section 8 summarises the future work plan and outreach activities

More information is available on our website: www.imperial.ac.uk/urbanenergysystems

2. Background and Project Plan

The original plan was organised into three partially overlapping phases (Figure 1). The first phase (2006-2012) was concerned with identifying in broad terms the potential of the proposed modelling and optimisation approach while later phases will address design and implementation.

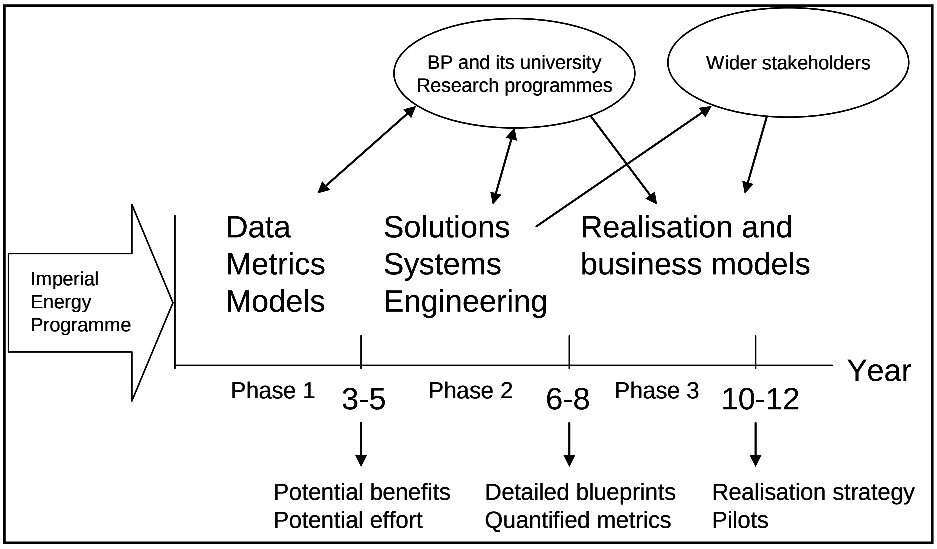

Figure 1. Original project plan

This has since developed into a “rapid prototyping” approach which was felt to be more productive. We have developed a prototype methodology that embodies the key concepts and then expended (and continue to expend) much more effort than initially planned on demonstration and testing activities, validated against hypothetical, existing and planning developments. The project plan has changed in that activities associated with phases 1 and 2 will start to take place in parallel, with case studies and demonstration projects taking place sooner (and hence earlier involvement of wider stakeholders) and informing methodology development, as in the diagram below. We have therefore undertaken a series of validation activities and are now finalising the outputs of phase 1.

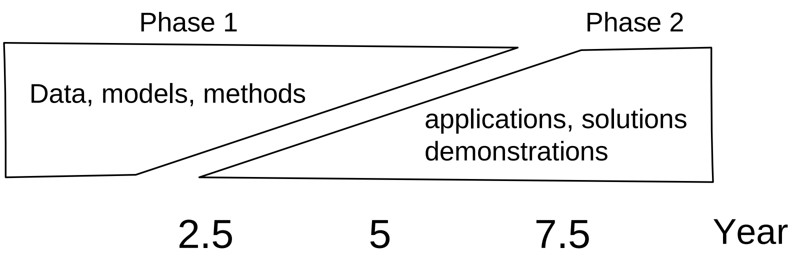

Figure 2. Revised project plan

As a result, we moved from solely undertaking high-level analyses to starting up some more detailed validation studies involving real, ongoing projects, and have been engaging potential end-users of the methodologies developed.

3. The Synthetic City toolkit

The Synthetic City toolkit has arisen out of our conceptual framework for the modelling of urban energy systems. It combines an integrated data management and simulation executive with four interacting modelling tools in a hierarchical framework, as in Figure 3**.**

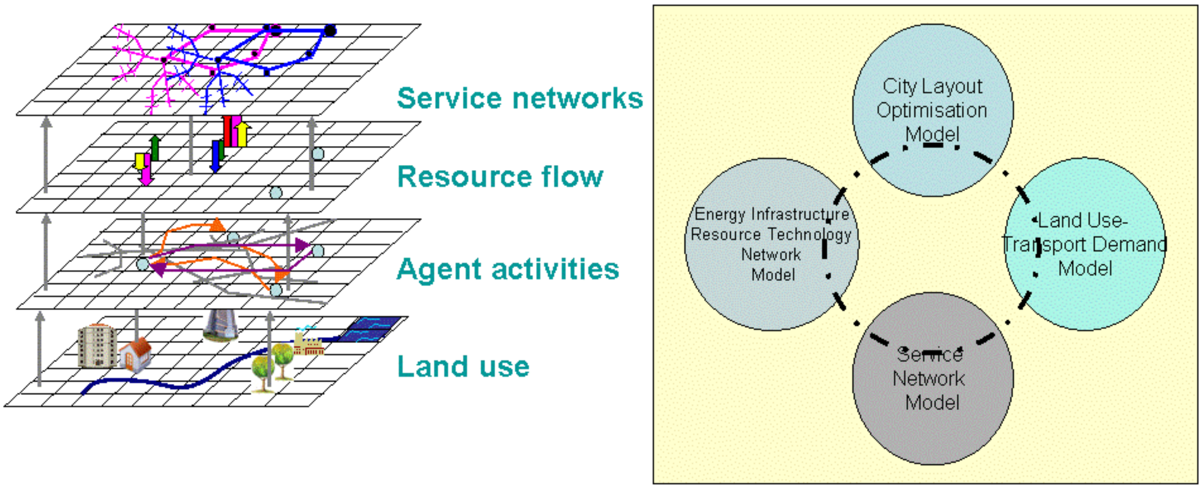

Figure 3. Hierarchical modelling framework

The main objective of the toolkit is to capture both the demand and supply aspects of urban energy systems. We believe that the toolkit's capability to look at the overall energy system of a city in this bottom up, integrated way is unique. It contrasts with other modelling approaches which tend to look at broader geographies (country, regional) and consider supply and demand independently and largely from a top-down perspective.

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The SynCity ("Synthetic City") modelling platform lies at the centre of the project's activities. The software consists of a Java code library, a database of energy technologies and fuels, and three connected submodels. Together these components enable users to explore the role of energy in urban areas at three significant stages: the master planning of a new development or redevelopment (the layout model); the daily demand-generating activities of individuals within a city (the agent activity model); and the design of energy supply strategies (the resource technology network model). Each component can be run separately or as a single integrated analysis and has been applied to case studies such as the design of a new eco-town; the feasibility of urban biomass energy systems; and the feasibility of urban waste to energy systems.

Each submodel generates its own results. The layout model, for example, provides a text summary of the solution including headline measures of cost and annual average energy consumption and carbon emissions. The output data can also be imported into a GIS system for the creation of maps. The agent-activity model currently provides an estimate of the annual average passenger-kilometres for travel within the city, as well as resource demands over time and within each zone of the city, which are derived from details about the activities undertaken by the city's population throughout the day at five-minute intervals). The resource-technology network model gives users a summary of the energy supply strategy including the supply technologies (e.g. which technologies are used, where they are located, what is their average operating rate), imports and exports to and from the grid, the structure of distribution networks within the city, and headline cost figures and other performance measures (e.g. GHG emissions). For all models, the data is typically output as formatted text which is then post-processed to produce images, maps and so on. Taken together, the sub-models and the toolkit provide a unique capability in the urban energy systems arena.

The last eighteen months has seen the SynCity toolkit progress significantly from its early prototype form to a mature tool that can be used in a range of scenarios.

Most of the new software development has focused on two significant enhancements to the toolkit: the graphical user interface (GUI) and a new agent activity model

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SynCity GUI

During the past year we have been using the SynCIty Graphical User Interface (GUI) to reconstruct existing case studies modelling energy usage in European capital cities including London and Paris. These case studies are part of an internal program for testing and improving the user interface. This has led to a number of enhancements:

- Improvements to the input form layouts, menus, labels and instructions;
- The ability to change most scenario parameters directly through the GUI without having to use an ontology editor;
- Redesign of the main control panel for building and running scenarios;
- Redesign of the project management dialogue;
- The addition of an embedded web-browser as a documentation tool;
- Improvements to the visualisation layout and controls, including the ability to add maps or schematics as background images;
- New charts and summaries, and the ability to compare key performance indicators across scenarios;
- A new installer to simplify deployment on Windows computers.

The GUI enables users to construct and run basic scenarios without having to enter model code directly. The GUI uses the SynCity toolkit's application programming interface (API) to build integrated models of urban energy systems (**Error! Reference source not found.**)). The GUI provides an interactive framework for modelling, ptimising and visualising different aspects of urban energy systems with the SynCity sub-models for layout, agent activities and resource technology networks. The GUI can be extended with dynamic scripts for preparing input data. The GUI creates skeletal definitions of SynCity objects representing an urban energy system and dynamic scripts can then be used to fill in or replace the object definitions. As an example, a script could be used to import data for resource demands and household densities from an external source. Scripts are written in Groovy, a Java-like language, and can directly access the model building functions in the SynCity API.

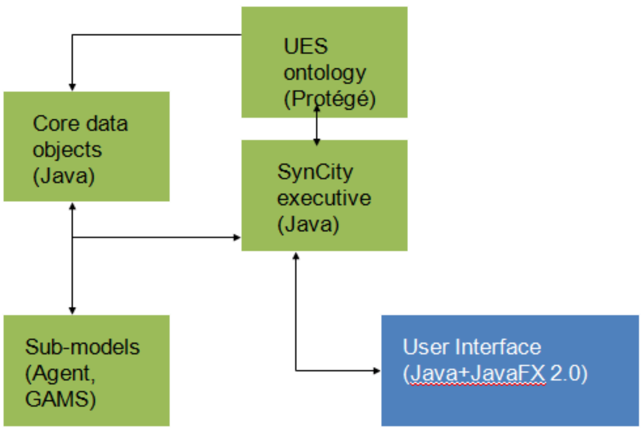


Figure 4. Interactive modelling framework for urban energy systems

The SynCity graphical user interface (**Error! Reference source not found.**) partitions a scenario into separate egments for the shared scenario data, parameters for individual models, and visualisation of the model results. Each segment in turn has tabbed displays for fragments of information such as the population parameters. The current release of the GUI implements the following features:

- Displays for shared scenario data such as population parameters and the layout grid;
- Displays for ontology objects such as infrastructure types, resources and conversion processes;
- Displays for specifying the parameters of GAMS models such as the RTN model;
- Visualisations that show resource flows and conversion processes as overlays on the city grid (Figure 6)
- Charts that display information such as resource demands and the optimal mix of conversion processes obtained from the RTN model (Figure 7).
- A control panel and console for initiating and monitoring SynCity model runs.

Our current development efforts are centred on the SynCity RTN model (Figure 8). We are planning on adding features that make it easier to change the objective function and constraints, extract key performance indicators, and to specify existing infrastructure locations directly through the GUI.

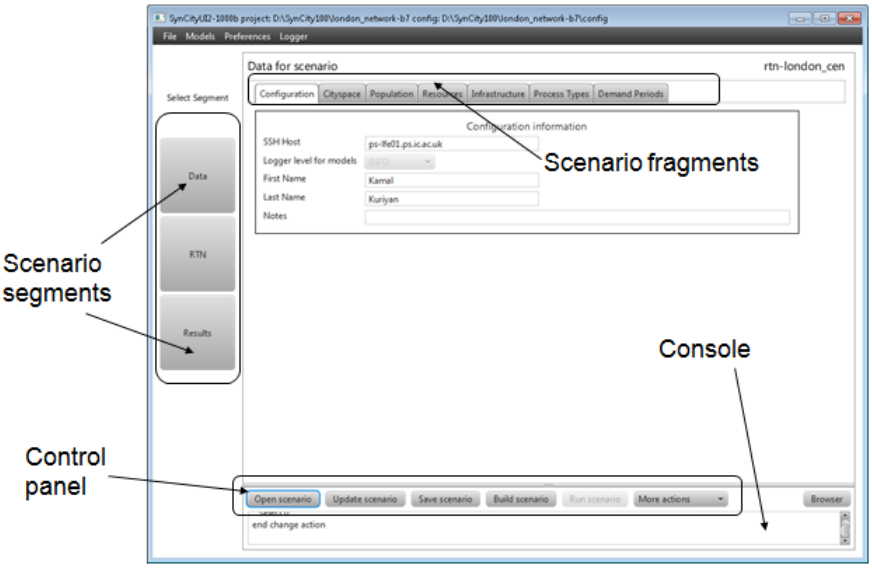
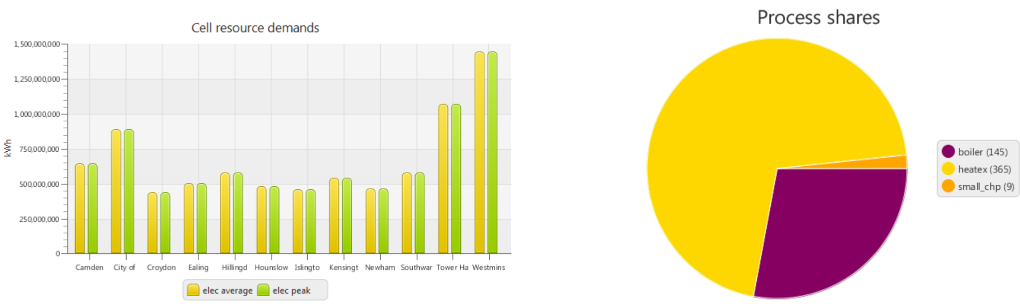


Figure 5. GUI for SynCity

Figure 6. Visualisation showing resource flows and locations of conversion processes.



Costs

Scenario	transport	storage	process	import	export	capital	objective
rtn-london_all	0	0	0	6.04438e+09	0	7.62130e+09	1.36657e+10
rtn-london_all_co2target	0	0	0	3.65772e+09	0	6.71336e+10	7.07913e+10
rtn-london_cen	0	0	0	8.63238e+09	0	1.82160e+09	1.04540e+10
rtn-london_dec_inc	0	0	0	6.01556e+09	0	7.56105e+09	1.35766e+10
rtn-london_dec_windren_no_inc	0	0	0	6.04430e+09	0	7.63990e+09	1.36842e+10
rtn-london_dec_windren_no_inc_customer	0	0	0	6.04439e+09	0	2.18424e+10	1.89686e+09
rtn-london_microdec_cashincentive	0	0	0	6.04436e+09	0	7.34749e+09	1.33918e+10

Figure 7. Sample charts and tables for SynCity RTN model

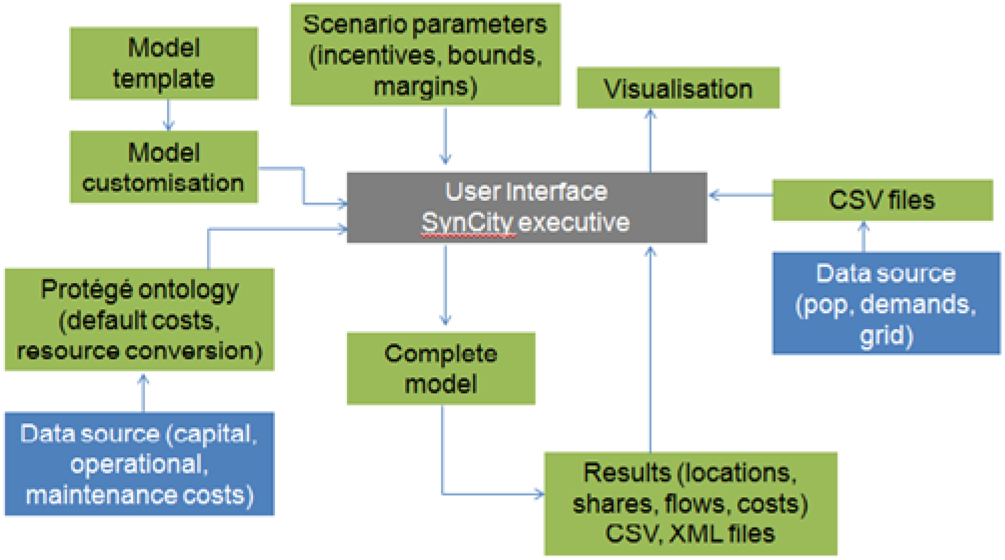


Figure 8. RTN model construction

Toolkit Applications

SynCity has been applied to a range of case studies, building both our understanding of urban energy systems and the underlying software tools. Highlights of this work include:

- A modification of the RTN framework to help Newcastle City Council plan their carbon emissions reduction plans. This involved modelling the potential benefits of energy efficiency technologies, renewable energy supplies, and district heating systems, drawing on high spatial resolution data about the actual building stocks within Newcastle. Working closely with the council and our collaborators, Newcastle University, we were performed a range of Monte Carlo simulations to show the impacts of policy uncertainty on emissions reduction goals. A paper based on this work has been submitted to *Energy Policy*.
- A comparative analysis of the impact of urban energy policy on energy systems performance in London, Paris, Berlin, and Copenhagen. This study looked at the diversity of existing infrastructures and policy incentives and highlighted the importance of local context in developing urban energy strategies. For example, combined heat and power is much less attractive in Paris than it is in Copenhagen owing to the low carbon intensity of French grid electricity.
- A journal article demonstrating how the layout model can be used in combination with Monte Carlo analysis techniques to develop minimum energy benchmarks for master planning
- Two journal articles based on the analysis of biomass energy supply strategies for a UK eco-town. The model's ability to consider a range of energy strategies is particularly valuable for biomass energy cases as there are a number of potential feedstocks and conversion processes.
- Two conference papers analysing the use of combined heat and power systems for a UK eco-town. One of these papers, focusing on how planning restrictions on CHP might affect urban energy efficiency, has been invited for journal publication.
- Working alongside a consulting engineer from Arup, we applied SynCity to Melbourne and the model's outputs helped to inform a C40 cities workshop on the benefits of "smart grid" technologies in managing carbon emissions. The second case study applied the layout model to a project provided by Foster and Partners. The aim was to discuss the model's relevance to traditional urban design processes and to see how the tool might be improved.
- Two student projects used SynCity as well. The first was conducted by a visiting researcher from China who examined heating and cooling strategies for a new development near Shanghai. This case helped to expand our technology database and test our tools in a non-European context. The other project was an analysis of Toronto's "Peanut District", an area of high-rise buildings targeted for redevelopment.

SynCity facilitated a detailed analysis of technology options and demonstrated that significant retrofit measures, together with a district energy system powered by low-carbon ground source heat pumps, offered the most promising solution for the site (see Section 5).

4. SynCity – component models

The four component models of SynCity and developments associated with them over the year are summarised below.

Layout model

This is an optimisation-based approach to organising the city layout. It is provided with the basic information about the city, its residents and boundary conditions, desired activities and so on, and uses a combinatorial optimisation technique to develop alternative city layouts. Different performance measures may be used for the optimisation.
Development status. This is a complex optimisation model which uses a two stage solution procedure where the layout model first calculates the position of the buildings and activities by seeking to minimize total travel. The second stage then determines the precise combination of transportation modes and passenger flows. This has been evaluated using a number of case studies and highlighted the tool's value as a method for calculating a benchmark minimum energy consumption for an urban area. In other words, while the resulting layouts may be impractical under commercial constraints, they enable developers to gauge their level of ambition and explore a range of alternative scenarios relatively quickly. Given the visual nature of the input and output, the prototyping of a user-friendly graphical user interface has been produced.

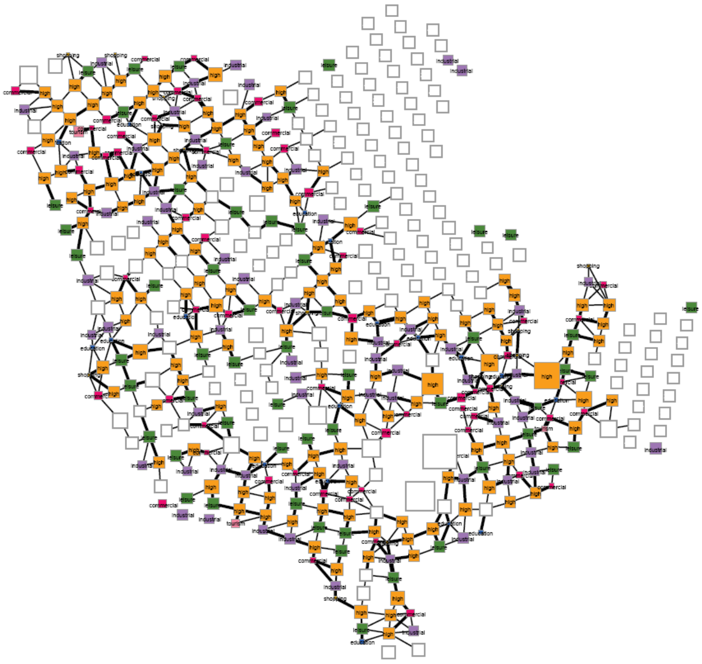


Figure 6. Example of optimised layout

Agent-based Micro-simulation Model for Urban Activities (AMMUA)

This model takes the city layout and establishes where the agents are at any given time and what activities they are involved in, and when they move between places their mode choices. This can then be used to infer time-dependent resource demands associated with the built environment (which can vary depending on building designs and standards) and the transport system.

Main developments. The short-term model system of daily activity-travel patterns in SynCity, which was previously a four-step travel demand model, has been fully replaced with a state of the art activity-based travel demand model system. We call this the agent-based micro-simulation model of urban activities (AMMUA), which forms the disaggregate demand modeling component of SynCity. This model combines the important features of agent-based micro-simulation modelling and state of the practice activity-based transport demand models. AMMUA therefore operates on individual agents (such as households, citizens, businesses etc.) with heterogeneous properties. The AMMUA model system comprises of sub-models such as activity generation models, scheduling models to determine spatial and temporal elements of demand, and urban goods and services models. It takes the city layout and establishes where the agents are at any given time and what activities they are involved in, and how they move between different activity locations i.e. with who, at what time of day and using what modes. This can then be used to infer time- and space-dependent resource demands associated with the built environment (which can vary depending on building designs and standards) and the transport system. This can also be used to assess the impacts of different compositions of vehicle fleets, private as well as company owned.

The initial developments in AMMUA were focused on the short-term models, specifically the activity generation, scheduling and mode choice models. Over the last year, we validated the Java implementation of these short-term models and developed other parts of the AMMUA framework including the Urban Goods and Services Model (UGSM), residential relocation models, a transport network model and a synthetic population generation module. These models were developed with the London case study as a backdrop. Figure 7 presents the overall modelling framework for AMMUA, and Figure 8 presents the detailed modelling framework for the UGSM component.

The objective of the UGSM is to predict transport flows related to B2B and B2C interactions as well as delivery and maintenance services such as mail, waste collection, plumbing and repairs. The first phase of the development of this model system is complete. Due to constraints on data availability we opted to implement the simplest version of this model system (analogical to the four-step travel demand model that was initially implemented instead of AMMUA). Also in order to overcome the data constraints we used a simulation environment for this implementation. The implementation demonstrates a proof of concept and can be easily extended as more data becomes available.

The residential relocation models serve to predict the medium term changes in the configuration of the urban population, as a result of demographic changes, real estate (re)developments, changes in real estate prices and other economic trends. These models are currently designed to be implemented in MATLAB, The transport network model is designed to translate the movements of people into flows on the transport network. This was developed using an open-source state of the art package called MATSIM.

The synthetic population generation procedure is still under development and should be completed by summer. When complete this will round out the capabilities of AMMUA as it is designed to generate a synthetic population for the urban area under consideration that is observationally identical to the real population along a range of multidimensional aggregate criteria. For example, the synthetic population can be designed to have the same distribution of households over space by household type (single person, couple, family without children etc), income and auto ownership.

We have also demonstrated the implementation of AMMUA through a couple of London case studies. The first study was aimed at analysing the impact of various transport pricing and peak spreading policies on the demand for resources – comparing the impacts on the actual layout of London, against the impacts on minimum energy and minimum cost layouts. The second study was aimed at examining the impacts of different vehicle fleet compositions (by fuel type) including personal automobiles, buses etc on the overall resource demands.

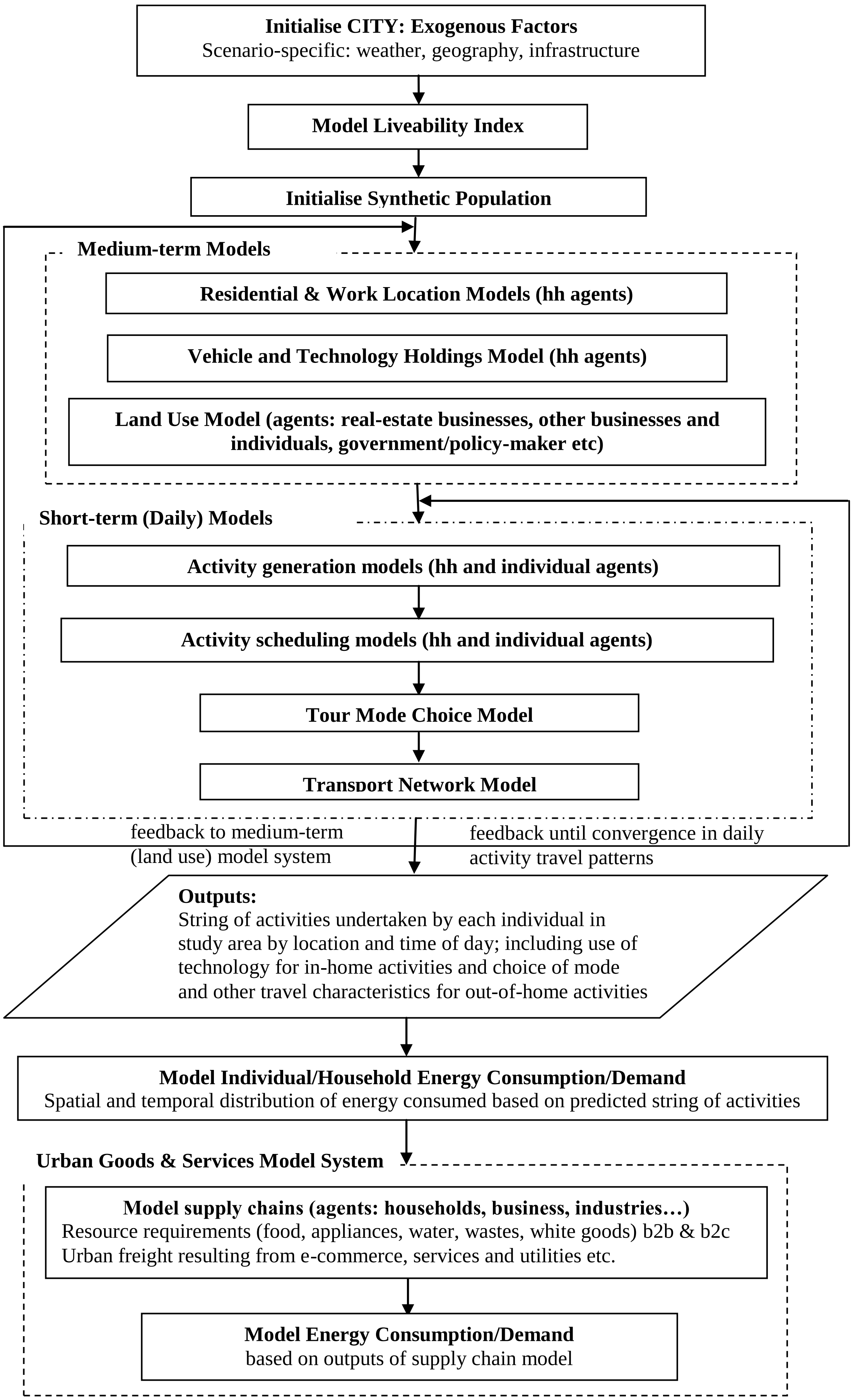


Figure 7. AMMUA modelling framework

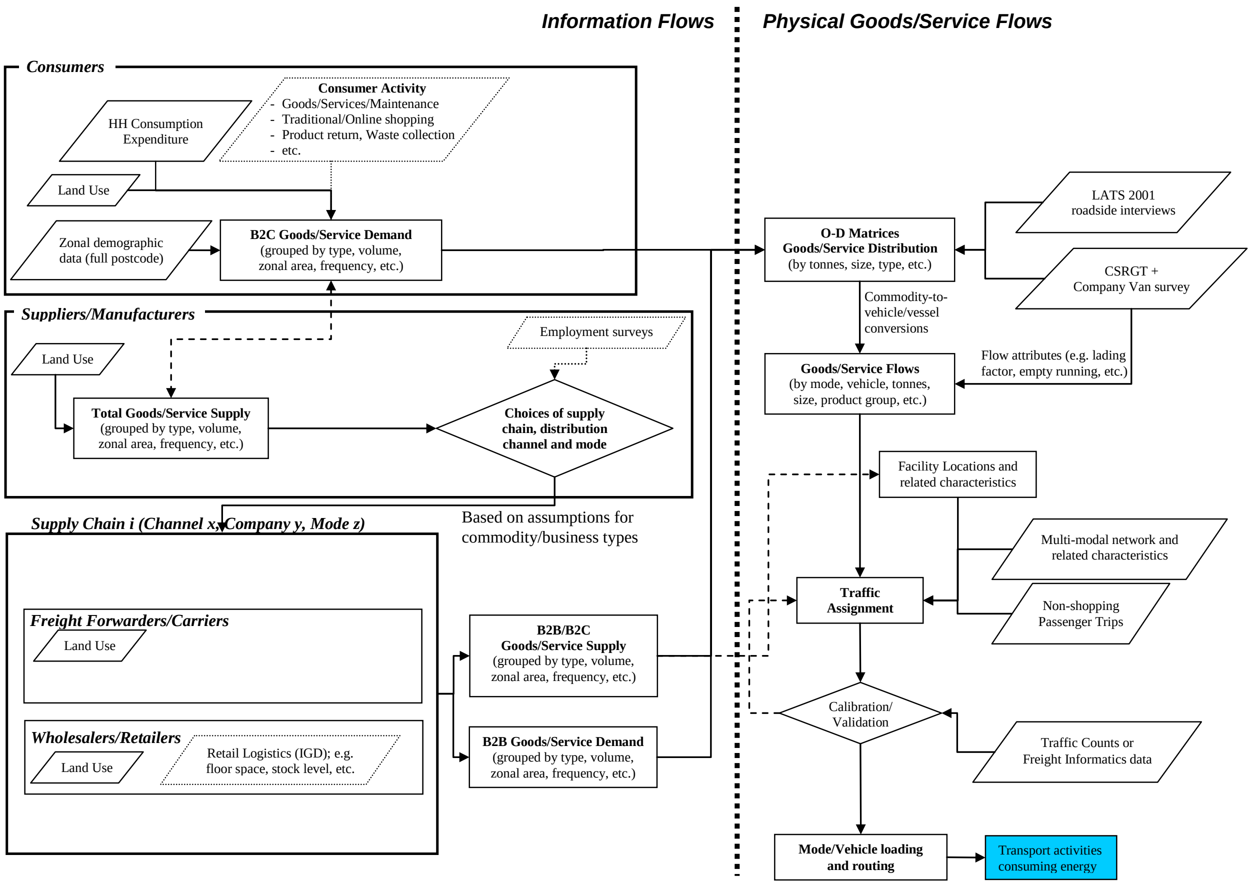


Figure 8. Framework for the UGSM

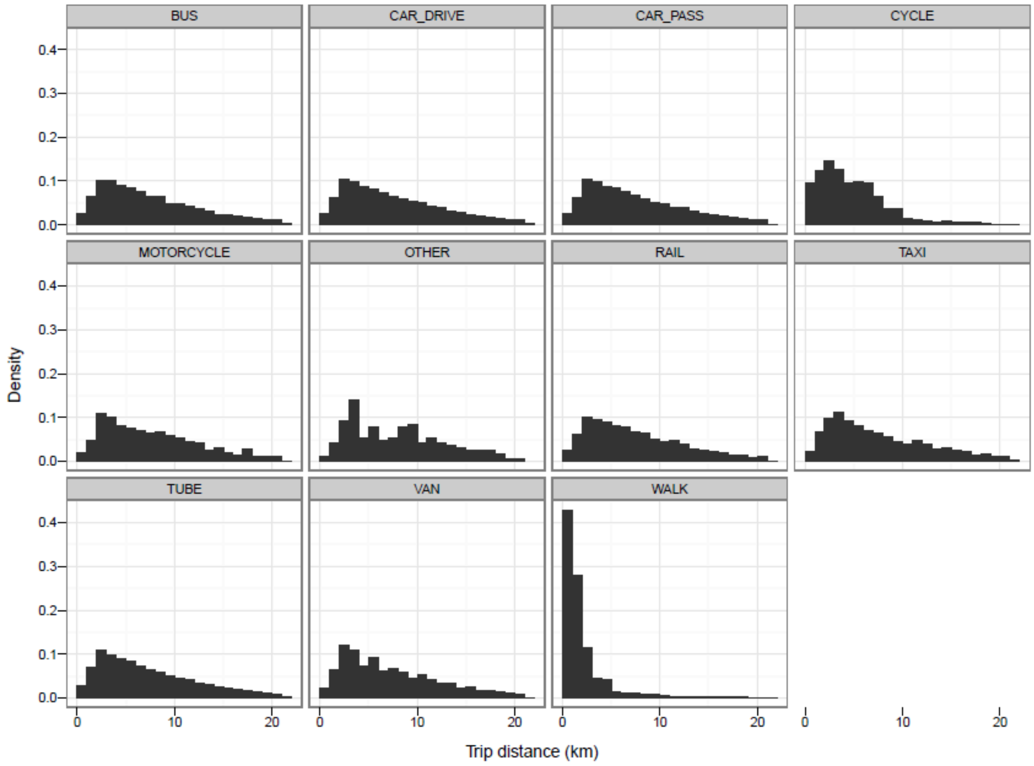


Figure 9: Trip length distributions by transport mode for the activities shown above. The new agent-activity model enables us to model such choices in greater detail, resulting in more precise resource demands in both time and space.

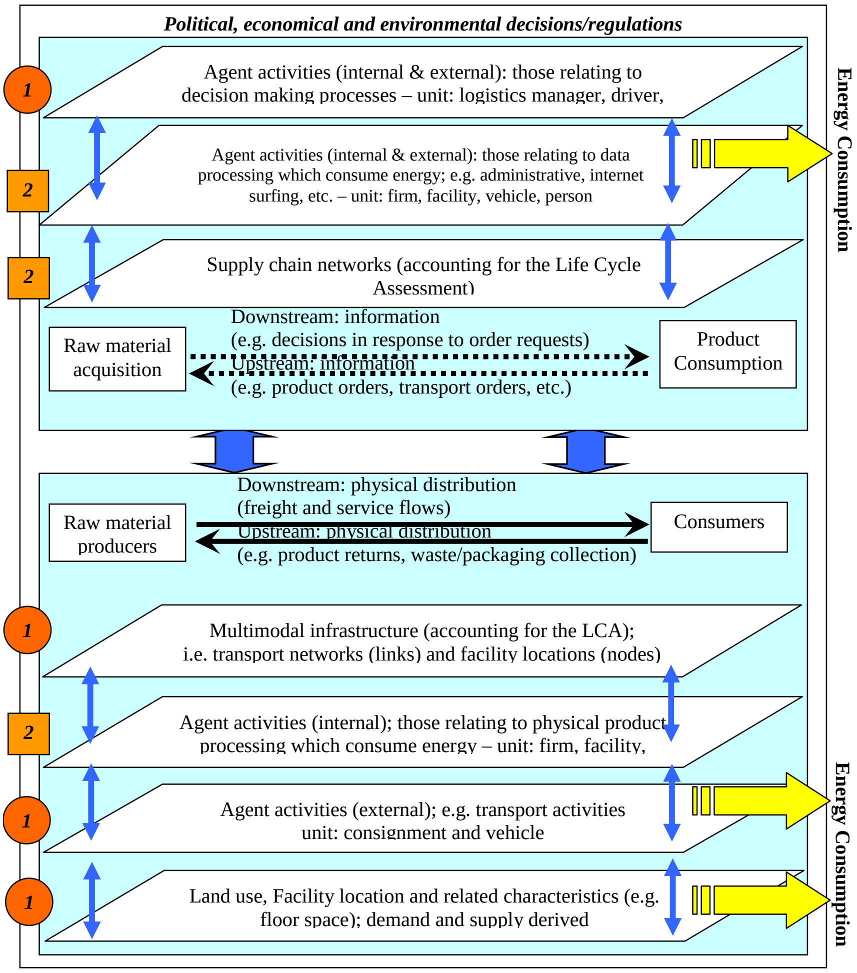


Figure 10. Conceptual Framework for the UGSM

Energy interconversion and infrastructure model – RTN

We use the novel “resource technology network” (RTN) model to determine how to supply the time- and space-dependent resource demands in an optimised fashion. The model’s degrees of freedom include:

- The choice of resources to import into the city
- The choice of resource interconversion and storage technologies and their scale to incorporate in the city
- The design of any networks for resource flow through the city
- The destination of wastes (including waste heat)

This uses a network optimisation algorithm based on mixed integer programming. Because it solves for all resource types **simultaneously**, it can automatically identify opportunities for integration across networks. Optimisation metrics can be defined in a flexible fashion and include capital cost, lifecycle cost, fossil energy consumption, GHG emissions, criteria pollutant emissions and so on.

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Main developments. Much of the recent work on the RTN model has been in testing and fine tuning the two-period (peak and average) model (designed for high spatial resolutions).

A number of case studies have been used to demonstrate the speed, robustness and flexibility of the RTN model. These include analysis of a UK Eco-Town under variety of energy scenarios: conventional grid energy, biomass energy and several strategies for converting municipal solid waste to energy, in comparison with landfilling. Another valuable study considers a large Eco-City in China (Lin Gang, next to the Yang Tze river) and the use of various heat pumps and trigeneration technology to provide electricity, heating and cooling. Energy systems were designed for minimum cost, minimum primary energy consumption and minimum CO2 emissions and the differences between the energy technologies and networks were quite insightful. These case studies have been presented at a number of conferences and full-length papers have been submitted for publication.

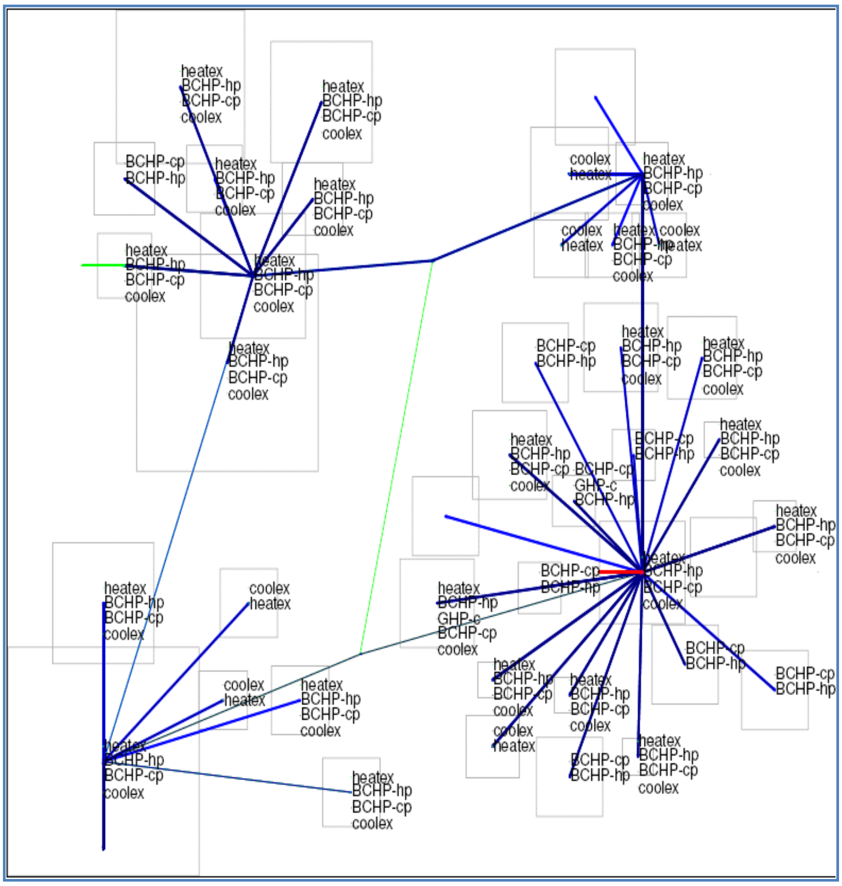


Figure 11. Energy network for Lingang New Town

The case studies were also used to identify and eliminate weaknesses in the two-scenario model, for example the objective function now accounts for pre-existing technologies (e.g. for retrofit case studies) and a new "household technologies" constraint was introduced to allow the model to treat domestic appliances more realistically.

Most of the improvements made to the two-period model are directly applicable to the full model. This is currently being written up for publication and the improvements are due to be implemented shortly. Further enhancements will include an integrated investment model and it is thought that this final model will be a unification of the three simpler models developed so far: that is, the simple long-term investment model, the full RTN model and the two-period model would all be special cases of the unified model.

Work has also started on a new model that is being designed to include all of the improvements made to the two-period model from the ground up. This also includes an explicit account of the types of buildings present in the city and which technologies they can accommodate. This could be the first step towards integrating the Layout and RTN models.

Service network design model

The resource flow network indicates the flow of resources between interconversion technologies and final demand points. It sets the target conditions for the actual service networks that must meet a variety of development of technical performance measures. The service network model is therefore concerned with the design of robust urban networks that embrace heterogeneity of generation and conversion and which incorporate the state of the art in the particular network type (power, gas, heat, etc.). Given that we anticipate greater integration, the interdependence between networks must be quantified and operational feasibility guaranteed.

Research has focused on assessing the detailed energy flows that occur in urban energy systems through key infrastructures such as electrical and natural gas networks. After establishing the principal guidelines of the time coordinated optimal power flow program; a modelling framework that considers the interactions and interdependency between conventional networks and embedded distributed energy resources (DERs), work has focused on strengthening the storage features of the embedded technologies. As a consequence, combined heat and power (CHP) units with thermal storage and plug-in hybrid electric vehicle (PHEV) units with battery storage have been included in the model. The representation of the possible power fluctuations that electric and natural gas can have in their nodes are illustrated in Figure 12 and Figure 13.

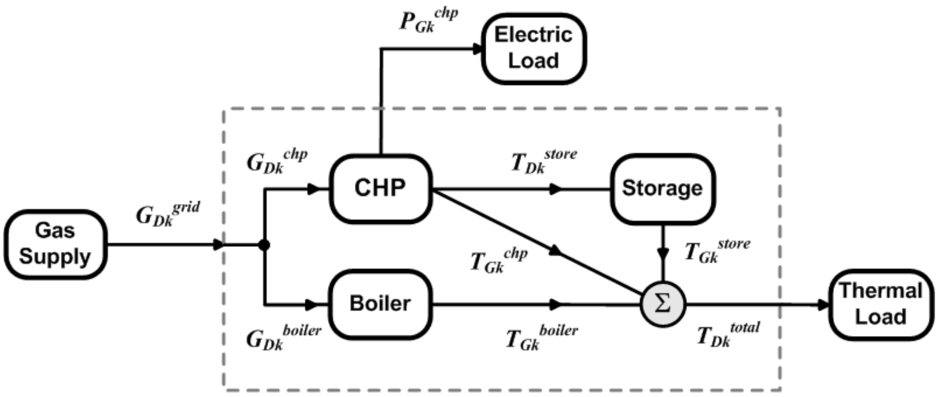


Figure 12. Within the natural gas nodes, the thermal power load can be satisfied by combining the flows from boilers, CHPs, and thermal storage units.

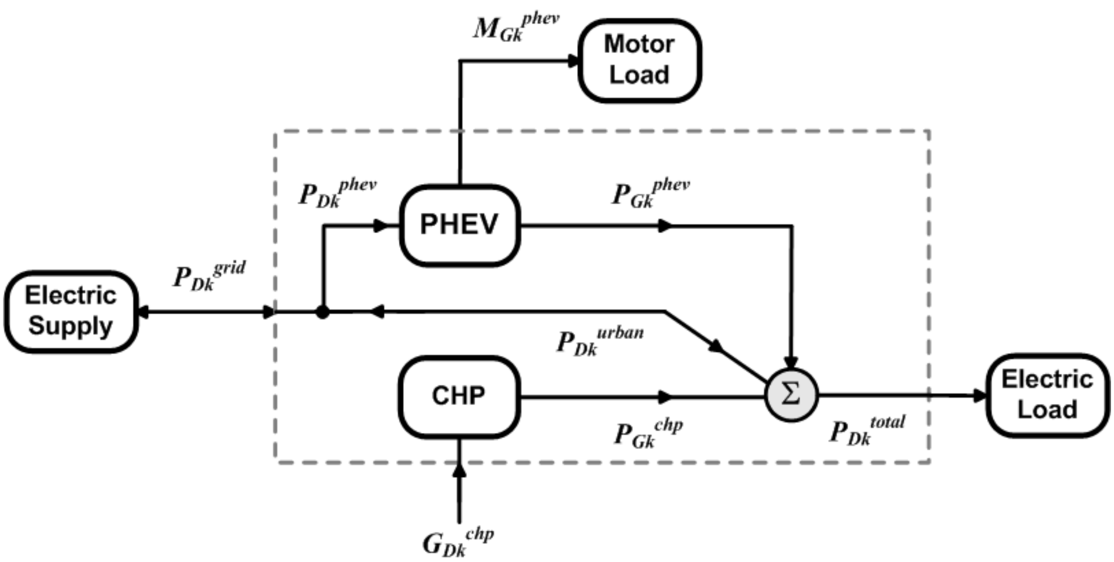


Figure 13. Within the electric nodes, the electric power load can be satisfied by combining the flows from the grid, CHPs, and PHEV units.

As Figure 14 illustrates, the flexibility in power provision through DER technologies allows the TCOPF tool to function as a global coordinator that can simultaneously evaluate the performance of natural gas and electrical networks; while dispatching DERs according to requirements of the stakeholders. Appropriately, in this research the optimal power flow program can be viewed as a body that enables demand response strategies. In other words, the TCOPF program takes the role of an intermediary, similar to an ancillary service provider, which sends operating signals based on grid conditions and the status of the connected embedded technologies. Furthermore, the modelling framework includes the feature of vehicles giving power back to the grid (V2G) if required.

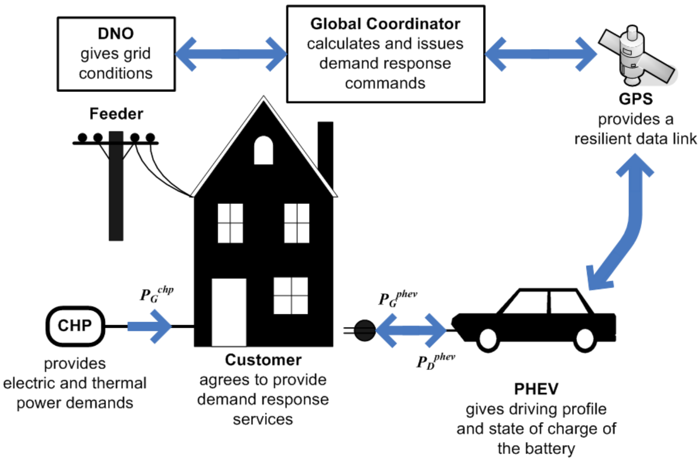


Figure 14. Communication architecture necessary to coordinate PHEV and CHP technologies for demand response services.

Modelling innovative interactions between new DER and energy infrastructures stimulates questions of optimal system operation, such as: "What pattern will DER profiles take according to different operating strategies?"

The TCOPF program considers the following objective functions:

- Plug and forget: refers to a status-quo scenario in which the DNOs just concentrate on supervising that the technical conditions of its assets.
- Fuel cost: consists on the economic dispatch of the units that can contribute with power generation, such that the total fuel cost is minimised while satisfying operational feasibility constraints.
- Energy loss: focuses on reducing the power losses incurred in the networks by dispatching the embedded technologies whenever it is necessary while meeting all operational requirements.
- Energy cost: approaches the day ahead natural gas and electricity spot market prices to reduce total energy costs incurred in the system while meeting all the demanded technical needs.

Case studies have been performed which have produced many outputs. These allow us to understand the trade-offs DER technologies and their peculiar operating strategies bring to energy service networks. Figure 15 to Figure 17 describe the operating behaviour DER technologies have under various formulations: plug and forget (gold), fuel cost (green), energy loss minimisation (blue), and energy cost minimisation (red).

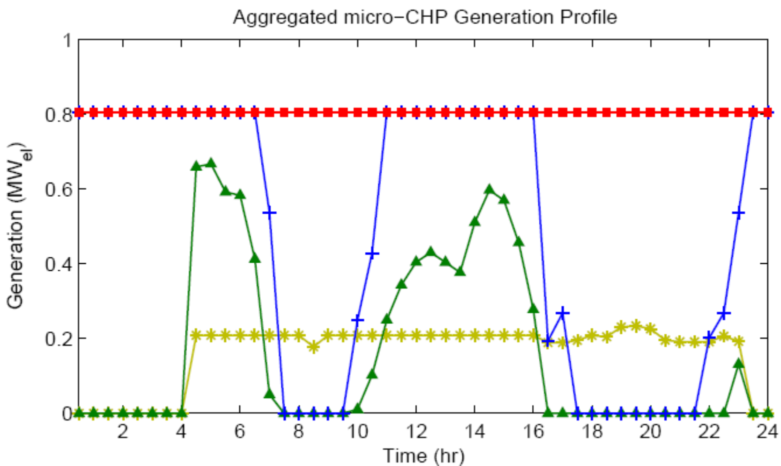


Figure 15. aggregated CHP electricity generation profiles obtained after applying a diverse set of TCOPF operating strategies – the units operate differently for each case

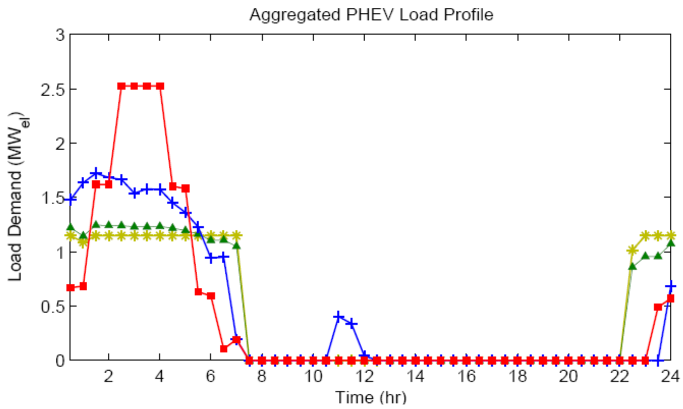


Figure 16. Aggregated PHEV load profiles obtained after applying a diverse set of TCOPF operating strategies – the units charge principally during the morning.

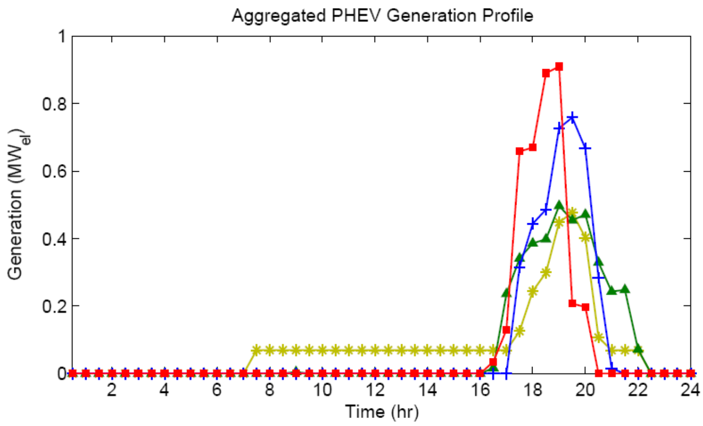
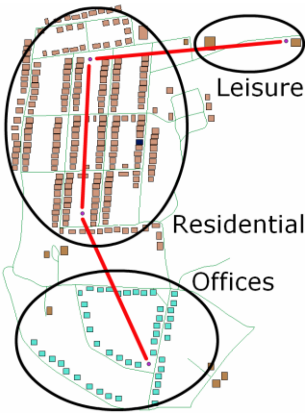


Figure 17. Aggregated PHEV V2G profiles obtained after applying a diverse set of TCOPF operating strategies – the units provide power principally during the evening.

The outputs obtained from running different simulations have been presented and published in two international conferences. In addition, a PhD thesis detailing the modelling framework developed has been submitted. Further work will involve increasing the level of detail in the model while also working in various case studies (e.g. eco-town developments) to identify common coordination patterns of the embedded technologies for different seasonal periods. Issues which will be addressed concern the inclusion of more DER technologies, agent based PHEV mobility features, and studies concerning power market and environmental topics.

We have also established a collaboration with the University of Delft in this area. We are working on an agent-based model of the behaviour of owners of plug-in electric vehicles in a city (built in Repast Simphony) which can be connected with a power flow optimisation model of the electricity distribution grid (built in GAMS) by providing temporal as well as spatial demand patterns. The link between the two models will showcase how different infrastructures in a city are related (in this case road and electricity) and allows for spatial analysis of vehicle charging and the effects on the distribution grid. The results of this first case study (see Figure 18) will be submitted to CIRED2011.



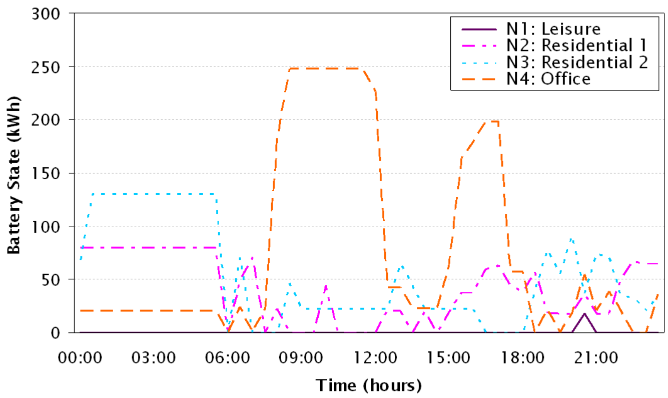


Figure 18. The 11KV distribution network with 4 substations in a city layout populated by owners of electric vehicles (left) and the state of charge of the battery of electric vehicles over time and space for each substation (right).

5. Some highlights

Case Study – Melbourne C40 analysis
For this study, ahead of the C40 UrbanLife workshop (facilitated by Arup), we divided Melbourne into the nine regions within the Northern Alliance for Greenhouse Action (NAGA), encompassing a population of approximately 960,000 people. Three scenarios were run:

- *Current practice*: Demands were specified from NAGA regional carbon accounts, with heating and cooling provided by domestic gas boilers and air conditioners.
- *Low carbon*: This scenario has the same demands as the Current Practice case, but we have introduced the 206 MW of renewable electricity potential (based on the average Victoria capacity in 2005). Electric heating technologies were added to facilitate the switch from natural gas to green electricity.
- *SmartCity*: Arup postulated that the introduction of "smart" technologies would enable reductions in demand throughout the city. These savings were assumed to be: 10% average, 20% peak reduction in stationary demands, 5% on transport demands. The technology mix is the same as the Current Practice scenario.
- *SmartCity + low carbon*: A combination of the Smart City and Low Carbon scenarios.

The results, shown in the figure below, indicate potential carbon savings of 62% in the low carbon scenario, 13% in the Smart City scenario, and 69% in the SmartCity/Low Carbon scenario.

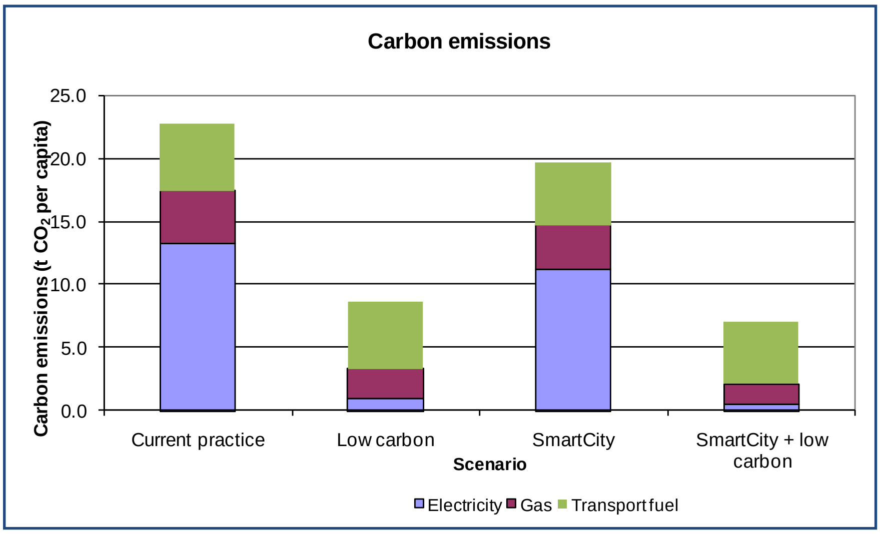


Figure 19. Comparison of CO2 emissions by scenario

Case Study – Meeting Newcastle's 2050 Carbon Targets

Working with the University of Newcastle and Newcastle City Council, we developed an alternative formulation of the RTN model to address the question: how can Newcastle City Council achieve an 80% reduction in carbon emissions by 2050? The motivation for this study was that, although the Council has previously modelled an indicative emissions strategy, they were unsure how the reality on the ground would affect the implementation of this strategy. For example, how many buildings in Newcastle actually have cavity walls that could be insulated? What would this mean for supply-side interventions like district heating?

To answer these questions, we modified the RTN model to consider a series of investment decisions between 2008 and 2050, encompassing both demand-side efficiency measures and supply-side technologies like renewable and combined heat and power. Running this model provides development pathways such as the one shown below, highlighting the importance of immediate improvement in efficiency, and long term shifts to low carbon supply sources.

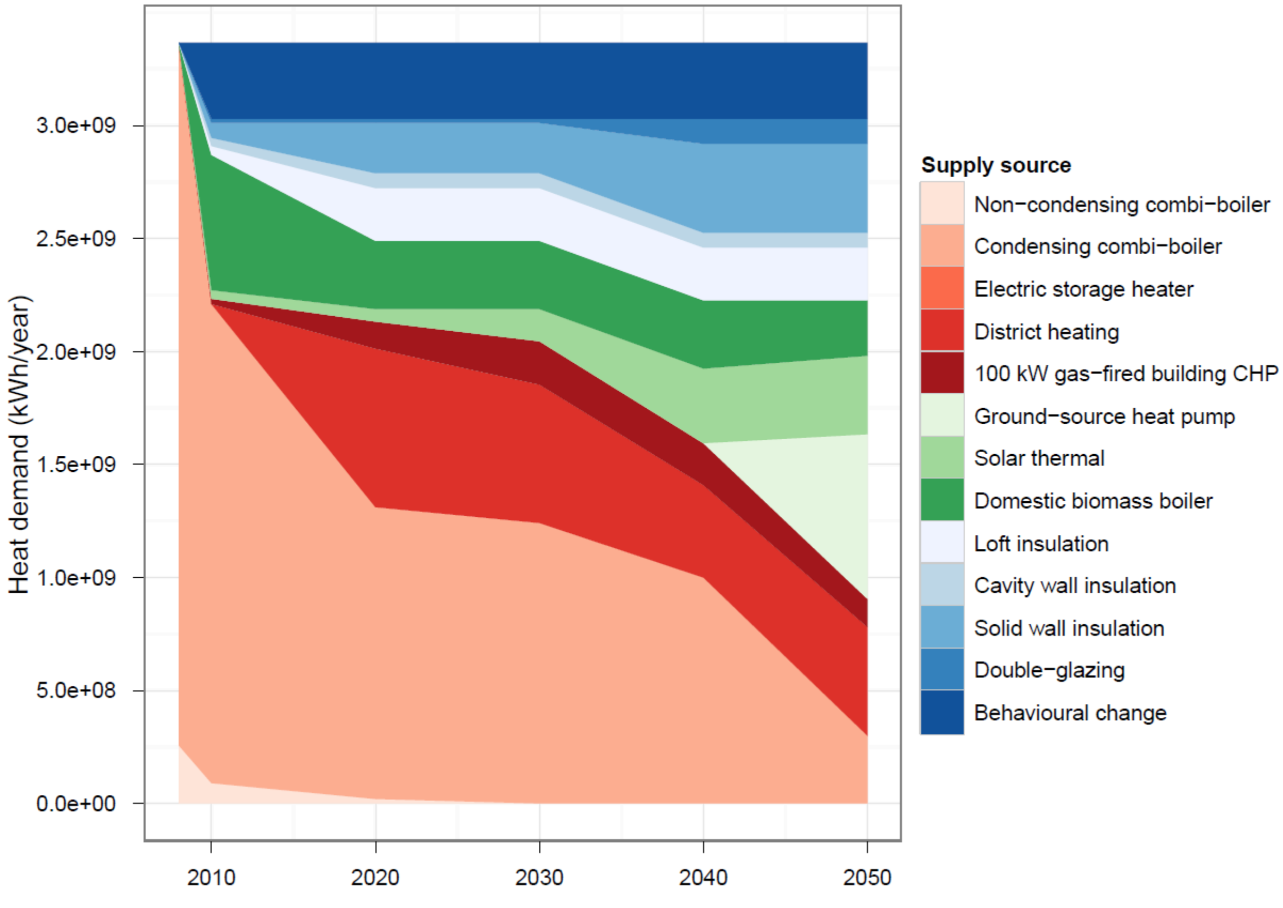


Figure 20. Provision of heat over time

However this result is for Newcastle as a whole. One of the key features of the RTN model is its ability to consider the spatial layout of a city. We therefore used data from the UK Home Energy Efficiency Database to estimate the building condition and potential of technology installations for a specific district within Newcastle. This provides a much more realistic estimate of the potential improvements. Furthermore we combined these assessments with an uncertainty analysis, to illustrate to the city council how uncertainty around key assumptions and policy decisions might impact the resulting solutions. For example, estimating a range of discount and inflation rates, as well as policy constraints on the maximum amount of CHP that could be installed in a region, we were better able to understand the penetration of different energy efficiency measures. As the figure below shows, these results enable policy makers to identify the low-regret measures (e.g. cavity wall insulation below, which is reaches full penetration by 2020 with very low variability) and those that may need more exploration (e.g. double-glazing which begins to be introduced after 2030 with a great deal of variability),

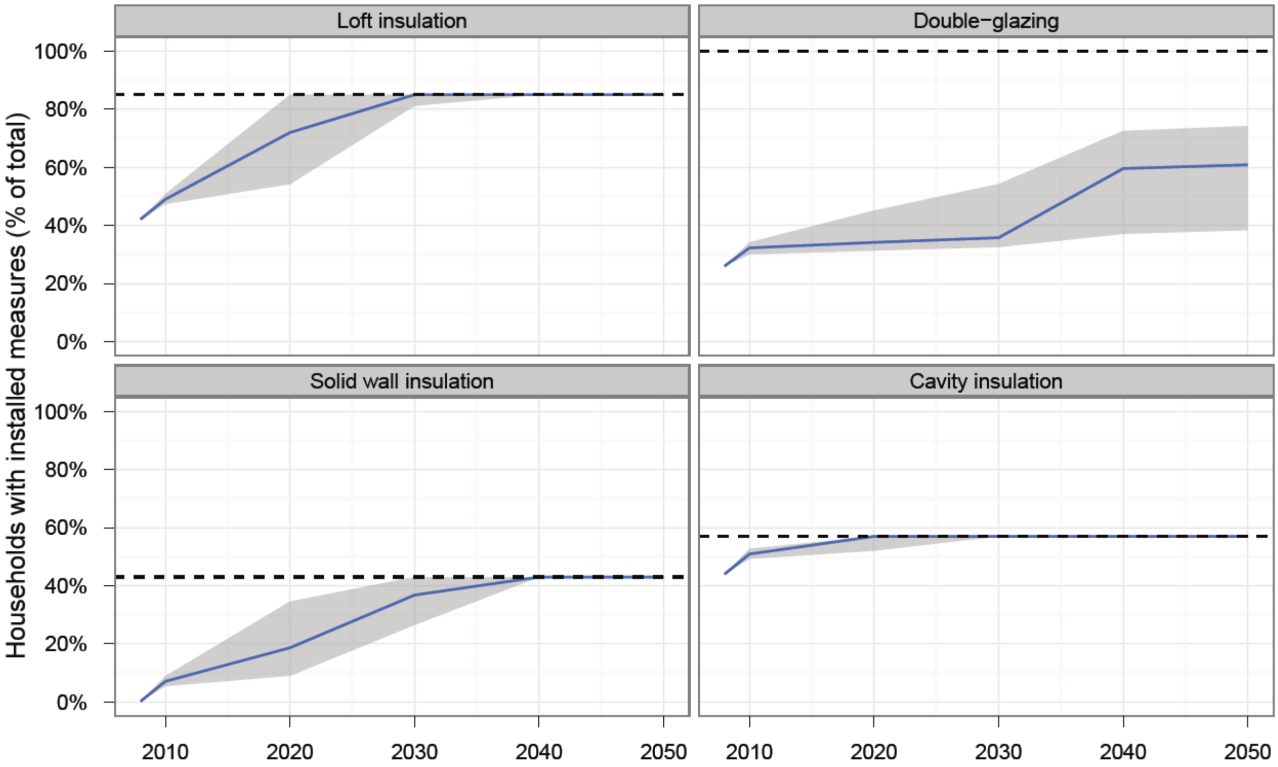


Figure 21. Installation of energy efficiency measures

Case Study – A comparative analysis of urban energy governance in four European cities

Cities are at the forefront of efforts to combat climate change and in this case study, we examined the influence of urban energy governance on these policy goals. An innovative framework for quantifying the combined governance of cities and energy systems is presented before focusing on a detailed study of London, Paris, Berlin and Copenhagen. By applying an optimization model to assess the lowest cost technology pathways to achieve emission reduction targets, the links between the governance of urban energy systems and the cost of achieving carbon targets are shown. Additionally a novel metric of scenario similarity is introduced in order to evaluate the difficulty of hypothesized energy system transitions. The results indicate that these tools can be valuable in identifying similar cities for the sharing of best practice, for performing comparative evaluations of energy transitions, and for reinforcing the need to complement quantitative assessments with a more holistic appreciation of local context.

Each of the four case study cities has ambitions to significantly reduce their greenhouse gas emissions, but the particularities of local governance arrangements influence the most cost –effective interventions. The urban governance metric and the optimisation results are illustrated below.

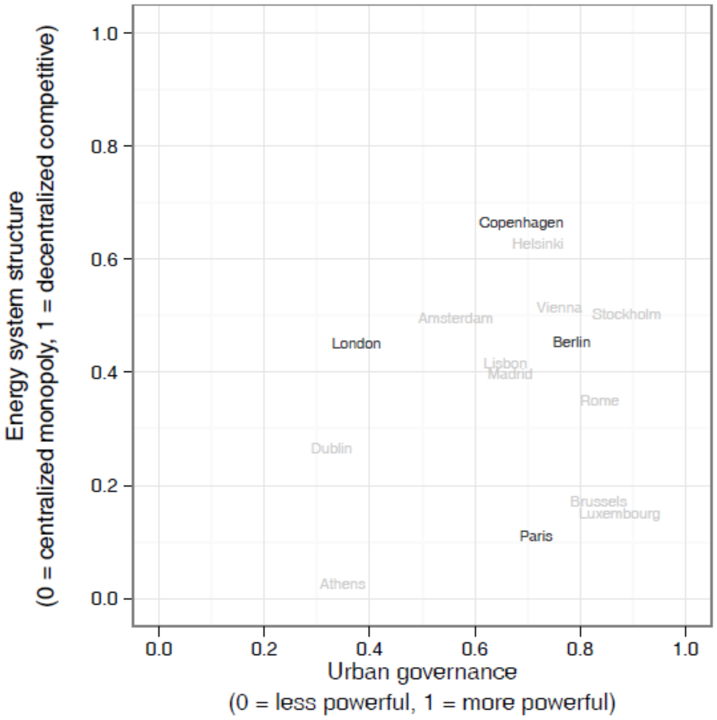


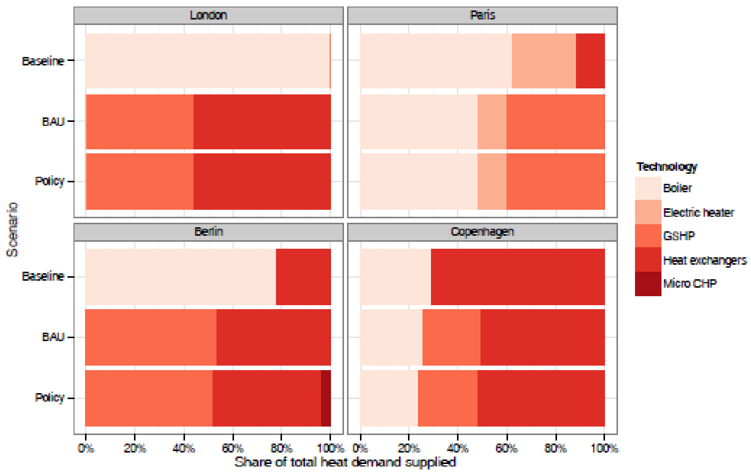
Figure 22. Comparison of governance factors in the UES for the EU-15 capital cities.

Each model was run in the BAU (minimum cost to achieve target) and Policy (solution constrained by current policy) configurations. The validation constraints on specific technology penetration levels were lifted so that the model had full freedom to achieve the carbon targets at minimum cost. This has the consequence of creating unrealistic implied transitions

in the energy system configuration (Figure 23). For example, heat is currently provided primarily by natural gas boilers in London whereas the BAU and Policy scenarios completely remove these technologies in favour of district heating and heat pumps. The overall analyses indicate that indicate that London faces the largest transition, particularly in the electricity sector, where no grid electricity is present in the 2020 cases; all of London's electricity needs are met by local generation. While this is clearly an unrealistic result from an operational perspective, it suggests that at current fuel prices it would be advantageous to generate more electricity locally from renewables and natural gas cogeneration. Paris is already very close to its ideal 2020 energy mix for both heat and electricity, whereas both Berlin and Copenhagen each have one energy service near the target (heat and electricity respectively) and another further away (vice-versa). By comparing the values against their respective governance metrics, one observes that the transition distance is greater for London, a city with much less urban power than the other three cities. Energy systems governance has less in influence, although Paris clearly benefits from France's already highly decarbonized electricity grid.

City	2010 Observed	2010 Validation	2020 BAU	2020 Policy
CO_2 emissions (tonnes per capita)				
London	4.80	5.04	2.44	2.44
Paris	3.37	3.36	2.35	2.35
Berlin	5.12	4.95	2.96	2.96
Copenhagen	4.21	4.12	0.90	0.86
Costs (billion GBP)				
London	–	10.5	57.0	61.4
Paris	–	3.79	3.71	3.50
Berlin	–	7.01	11.3	11.3
Copenhagen	–	1.54	1.46	1.36
Abatement cost (GBP/t carbon)				
London	–	–	2290	2510
Paris	–	–	−39.6	−133
Berlin	–	–	629	622
Copenhagen	–	–	−7.9	−15.9

Table 1. Summary of 4-city modelling results



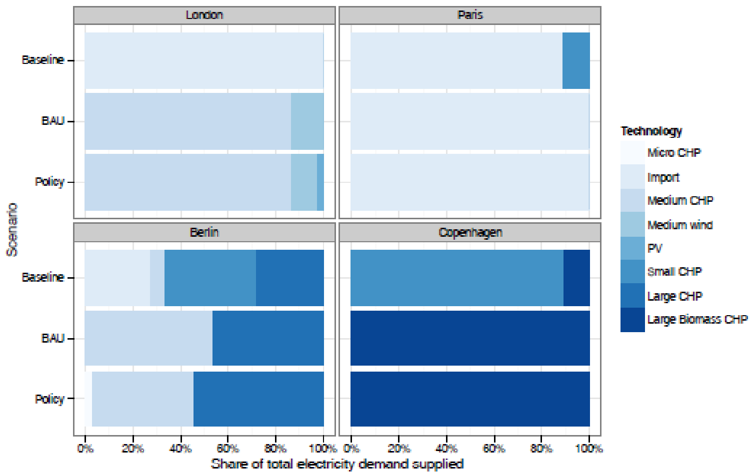


Figure 23. Technologies used to supply heat (read) and power (blue) demand for each city and scenario

To summarise this, we created metrics of urban and wider energy governance based on existing data sources On their own,

these metrics appear to be valuable as Figure 22 enables clear discrimination between the various capital cities of Europe and the results are confirmed by describing the chosen case study cities in greater detail, showcasing for

example the differences between London's centralized market-driven energy sector and limited local power and the more decentralized approach seen in Copenhagen. Such a figgure can therefore be used to assess the initial prospects for transferring best practice in urban energy policy from city to city. For example, there appear to be great similarities between cities like Brussels and Luxembourg, and Lisbon and Madrid. These indices were intended to provide a general framework for comparing the urban energy governance of cities. However there may be value in extending these metrics to recent specic policy goals such as climate change mitigation, as considered here. Taking Paris as one example, the prospects of this city meeting its carbon reduction goals look promising, as measured both by the similarity of energy supply technologies in the baseline and the BAU and Policy low carbon scenarios, and by the negative abatement costs of meeting these targets. This might lead one to conclude that powerful cities located in highly consolidated centralized energy markets are best able to meet their climate change goals. In fact it is France's decision to pursue low carbon nuclear power that has made this particular urban energy policy goal possible. Other cities with similar urban and energy governance scores may struggle if the centralized national technologies are, for
example, coal-fired power stations. These metrics are therefore a first step towards understanding a city's potential to meet energy policy goals, but they should be refined to reflect the analyst's specific interests and combined
with general knowledge of the study location.

Agent-based simulation of London's resource demands

For this analysis, we used the new Agent-based Microsimulation Model for Urban Activity (AMMUA) model to estimate the demands for heat and power in London. We first gathered reference data representing current practice in London. The spatial distribution of these demands is shown in the figures below and result in annual greenhouse gas emissions of 9.1 t CO_2 per capita.

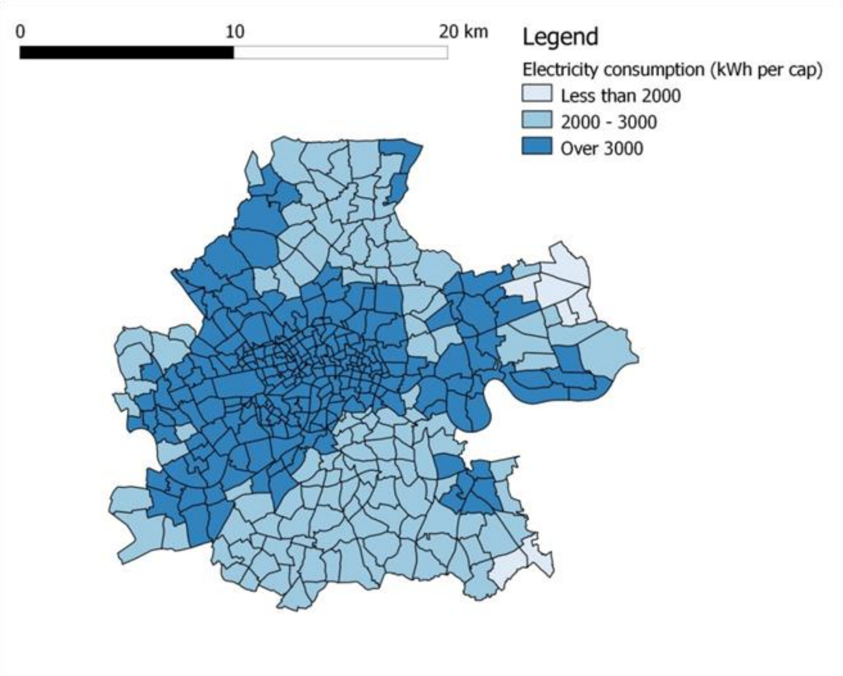


Figure 24. Estimated electricity demands for London

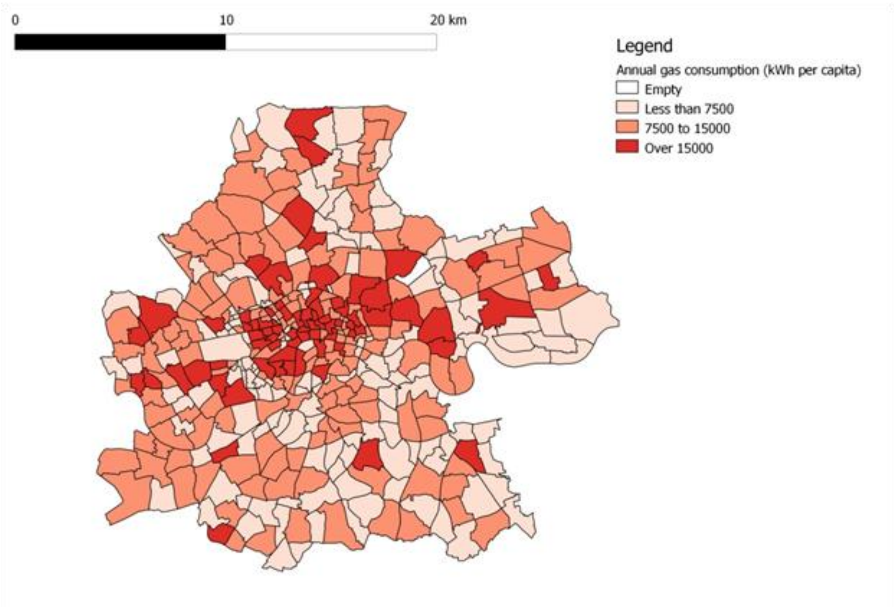


Figure 25. Estimated gas demands for London

Using land use patterns from the London Transport Survey, we then simulated the demands using the AMMUA system. The overall level of carbon emissions is very similar, at 10.0 t CO_2 per capita, however the spatial distribution of activities is slightly different.

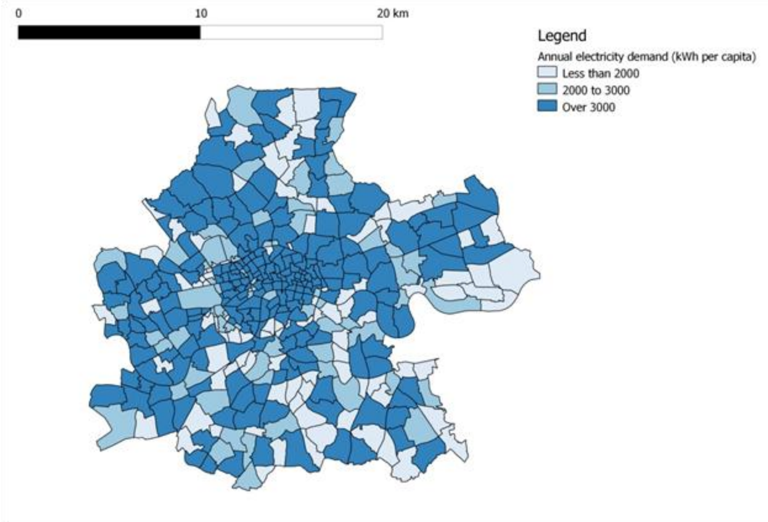


Figure 26. Estimated electricity demands based on actual land use patterns and AMMUA

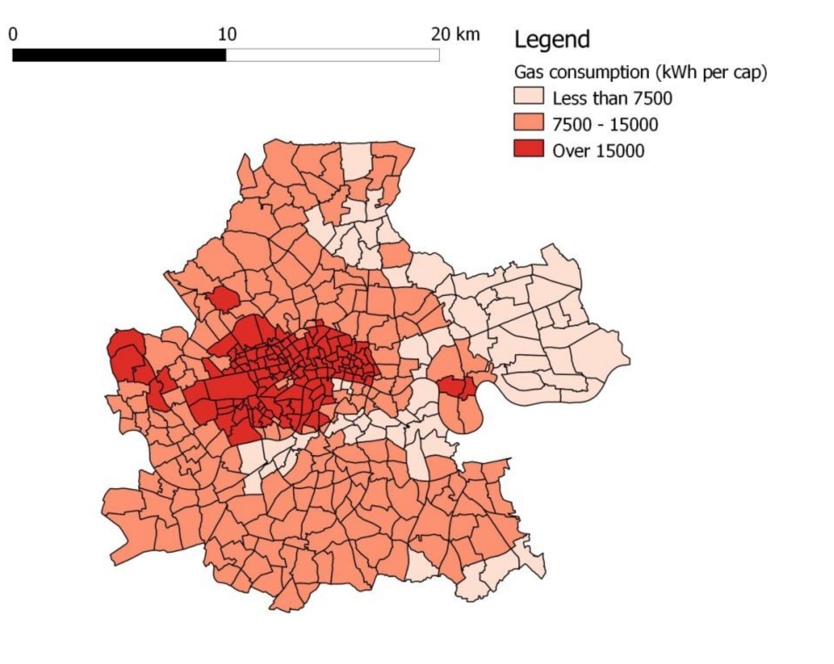


Figure 27. Estimated gas demands based on actual land use patterns and AMMUA

Finally we combined the AMMUA model with the results of an optimised urban layout. The layout model sought to provide the same level of activity provision and housing, but with the goal of minimizing lifecycle cost. The figures below show that the demands are more spatially concentrated, as in the observed London data (although with a number of empty sites), and the greenhouse gas emissions were 5.2 tCO_2 per capita. This is due to the increased use of high-density housing. The next step of this analysis will be explore the temporal distribution of the demands, considering how demand patterns might shift as a result of alternative commuting patterns (e.g. a more dispersed rush hour).

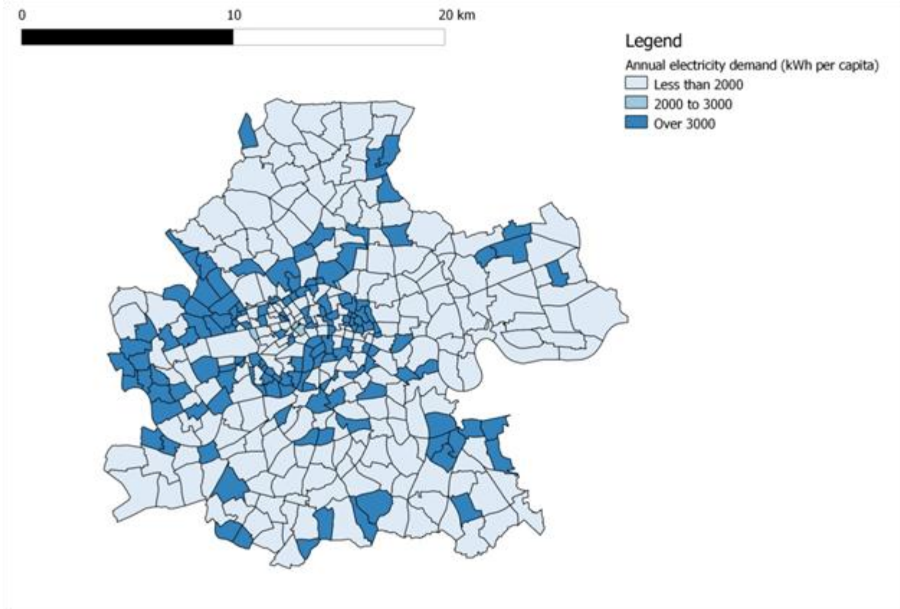


Figure 28. Electricity demands for compact layout

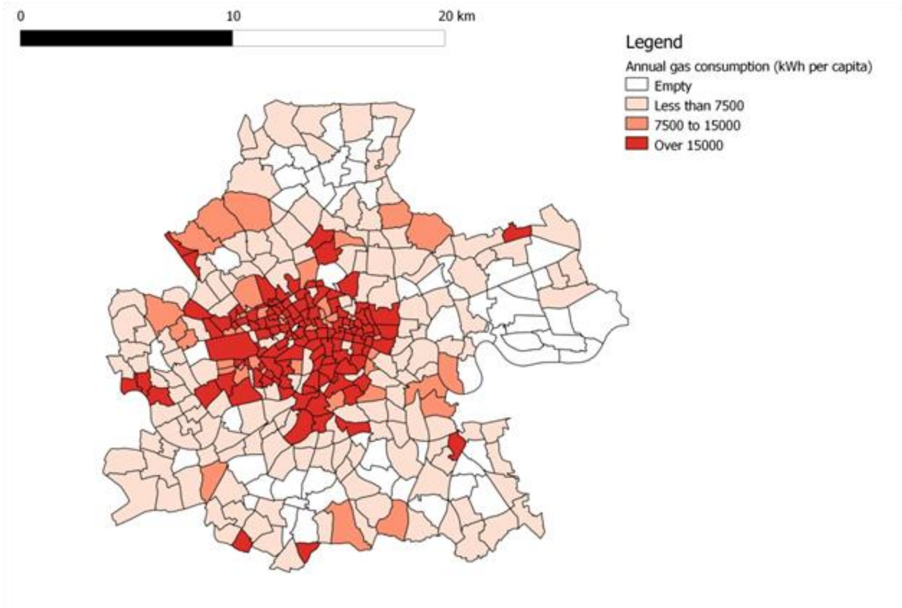


Figure 29. Gas demands for compact layout

Low carbon city design – Lingang New Town

The development of low-carbon cities is a topic of growing interest in China. The main feature of a typical Chinese low-carbon city is compactness: namely High-density, High plot ratio, High rise, or the city of “3H”. Particularly, it is impossible for China to follow the low-density, suburbanization and private car-led urban development patterns such as the United States. The energy plan goal of a Chinese low-carbon city is to achieve “3D”: namely Decarburization, Decentralization and Demand reduction. To achieve these three goals, it is necessary to achieve the first “D” through the energy planning of municipal level required (which may be called “big energy”), or low-carbon energy technology; to achieve the second “D” through the energy planning of the community level (which can be termed "community energy"), or scattered capacity; while the third “D”, or demand reduction, can be achieved through the energy-saving of end-use respectively. The terminal energy-saving is also seen as a “virtual energy”, as a carbon-free resource supporting regional energy planning.

Lingang New City, which involves the reclamation of land from sea, is planned to be the industrial, economic and cultural centre of southeast coastal Shanghai. It is linked with the biggest deep-water port in China, Yangshan Port, through a 32km-long bridge and is only 72km from downtown Shanghai. The Shanghai government has planned to make it serve as a Low-carbon demonstration zone, together with Dongtan Eco-city and Hongqiao New City. The Master Plan of Shanghai (1999-2020) aims to build Shanghai as one of the international centres of economy, finance, trade and shipping. Planning is divided into four regions: the central area (the main city), the main industrial areas, mixed-use zones, and the heavy equipment industrial and logistics zone.

The main city will demonstrate the level of the new century's urban construction and environmental quality of urban life in a landmark district. The total area is 74.1 square kilometres, 36.3 km^2 of which is urban construction land. The "drip Lake" (5.6 square kilometres) is planned as the core, expanding outward in the form of rings and radiation. The main focus of this area is Lingang New City's municipal public services and urban residential area. The main industrial zone has a total area of 101.6 square km, of which 57.1 km^2 is urban construction land.

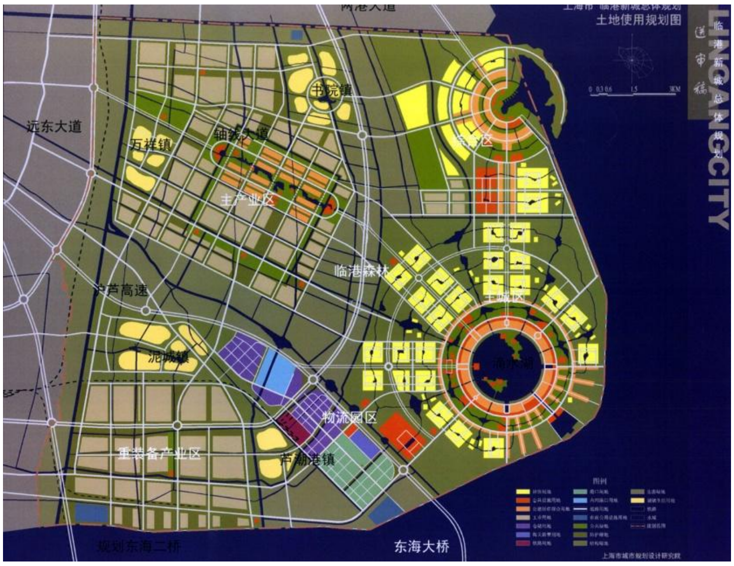


Figure 30. : Master plan of Lingang New City. 1: Main industrial area; 2: Mixed-use zone; 3: Heavy equipment industry and logistics zone; 4: Main city

The plans include modern equipment industry, export processing industry, high-tech industries and an appropriate amount of education, research and development zone and other comprehensive function zones, such as commercial office space. In addition, the main industrial area also includes two towns as living areas named "shu yuan" and "wan xiang".

The mixed-use zone is an integrated functional area based on urban ecological construction and high-tech industry with the lowest development intensity, highest environmental requirements and ecological optimum of the four major urban plots. The total area is 42.1km^2, of which 19 km^2 is urban construction land. The plan here is to establish high-tech industry, education, research and development, tourism, vacation, leisure and residential and commercial service oriented buildings.

The heavy equipment industry and logistics zone is the second industry-dominated area, and also focuses on coordinated development with the coastal environment. The total area is 78.7 square km, of which 52.4 square km is urban construction land. This sector will include heavy equipment industry, warehousing, ports, terminals, customs and other; also including two towns as living areas named "ni cheng" and "lu chao harbour".

By 2020, Lingang New City will have about 830,000 residents, of which the urban population will be 810,000 and the urbanization ratio will be 95% with advanced manufacture industries. The urban population is mainly distributed in the central area (the main city), mixed-use zone, as well as the four living towns: shu yuan, wan xiang, ni cheng and luchao harbour.

We developed a SynCity model of the city and applied it to layout and RTN optimisation. After establishing the baseline master plan layout, the model sought to provide sufficient housing and activities for the estimated population on how these demands were met. The results are broadly similar, with the optimised layout demonstrating a higher level of connectivity between cells.

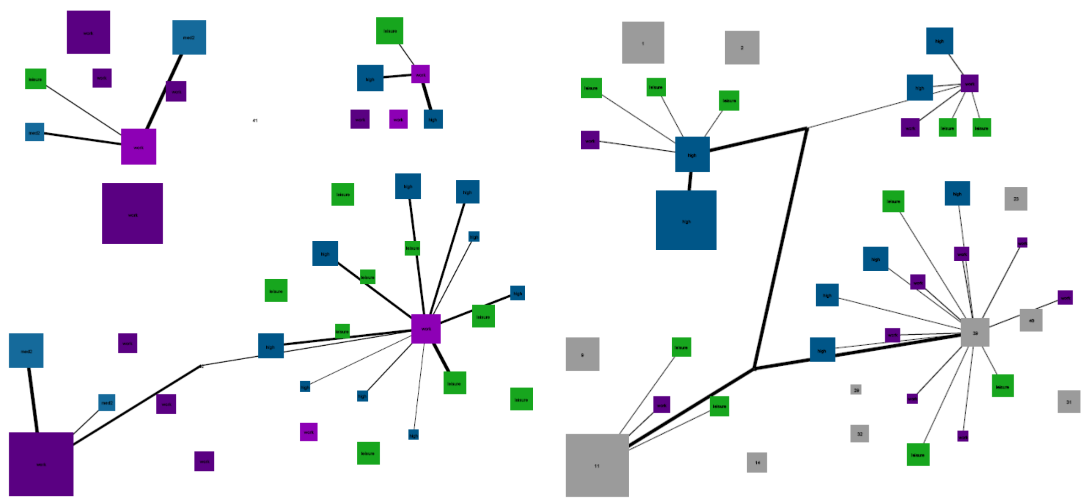


Figure 31. Layouts - as planned (left) and optimised (right)

Since the fully-detailed agent-activity model was under development, we calculated the demand of electricity, heating and cooling according some Chinese standards and codes. The results are shown in Figure 32.

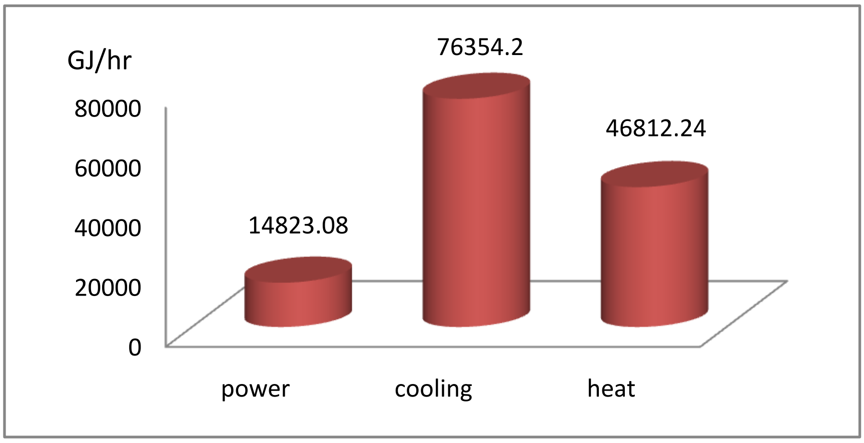


Figure 32. Estimated demands for power, cooling and heating

The resource-technology network (RTN) model is designed to select an optimal energy-supply strategy for a pattern of resource demands. Four different supply strategies are available to meet the resource demands: importing the resource from a hinterland, receiving transfers of the resource from another location within the city (i.e. via a distribution network within the city), creating the resource locally (e.g. by converting other resources) and consuming stored resources. The RTN model is used to minimise one of the following objective functions:

- Cost;
- Primary energy consumption;
- CO_2 emissions;
- A weighted sum of cost and CO_2 emissions (here termed “combined optimisation”).

We allow only natural gas and electricity to be imported into the city, each at only one location, so that a distribution network must also be designed to allow transfers of these resources to other city locations. Electricity demands can therefore be met by importing it and distributing it throughout the city and/or by using some of the technologies described below that are able to produce electricity.

We have compared 7 kinds of heating technology in winter, which are: gas boiler (boiler), electric heater (eheater), air source heat pump for heating (ASHP-h), ground source heat pump for heating (GSHP-h), gas engine heat pump for heating (GHP-h), gas direct-fired absorption heat pump for heating (AHP-h) and building cooling, heating and power for electricity and heating (BCHP-hp). During the summer period, 5 kinds of cooling technologies are considered: air source heat pump for cooling (ASHP-c), ground source heat pump for cooling (GSHP-c), gas engine heat pump for cooling (GHP-c), gas direct-fired absorption heat pump for cooling (AHP-c) and building cooling, heating and power for electricity and cooling (BCHP-cp). Note that the model considers two time periods, winter and summer, and that the *same* technology is assumed to be able to produce heat in winter and cooling in winter (with, of course, different coefficients of performance). Below are some of the results to for the CO_2 emissions minimisation case.

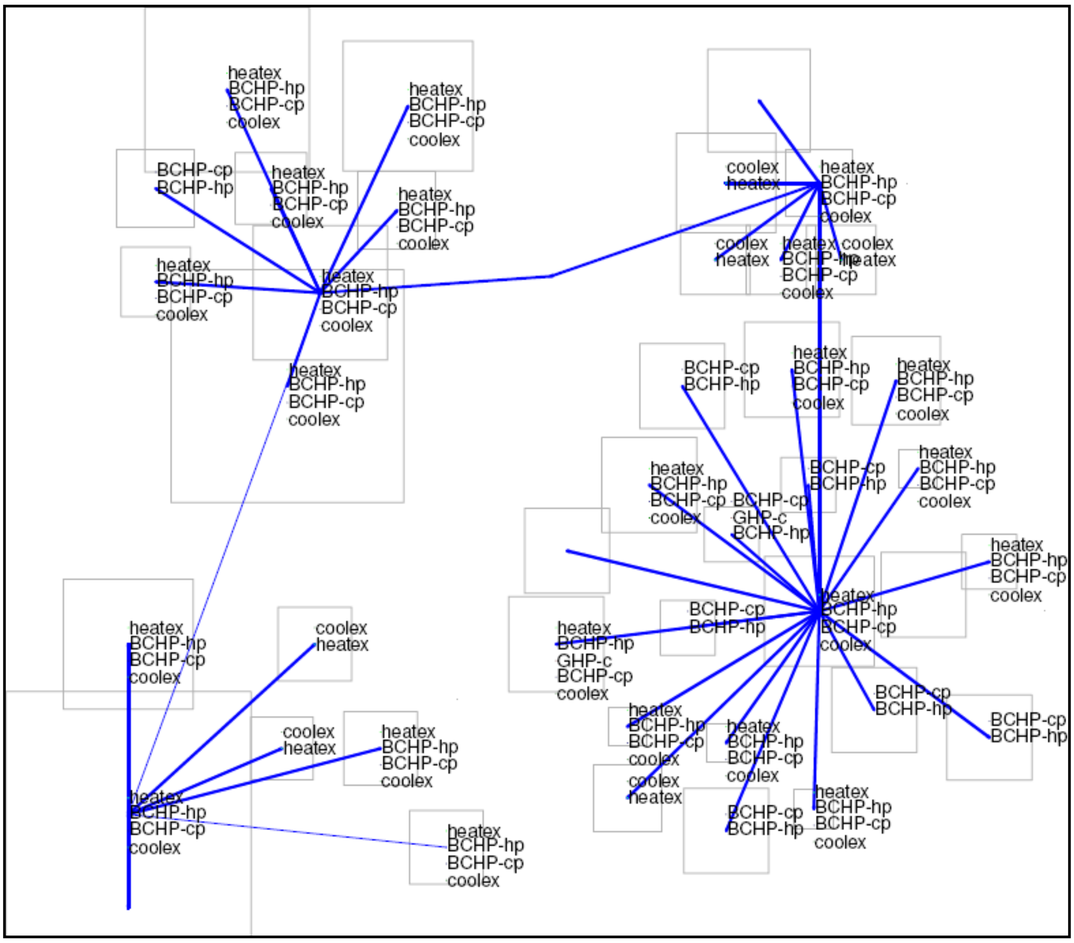


Figure 33. District heat distribution network for minimum CO2 emissions

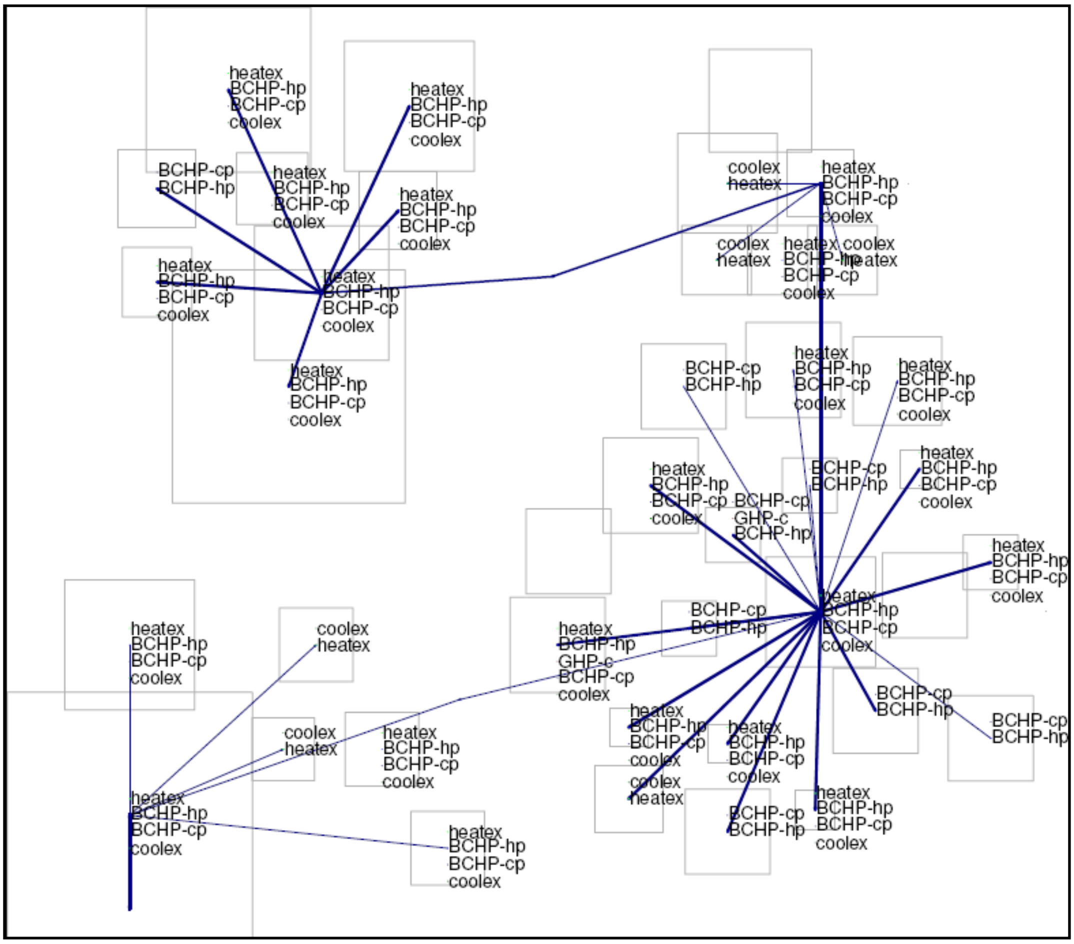
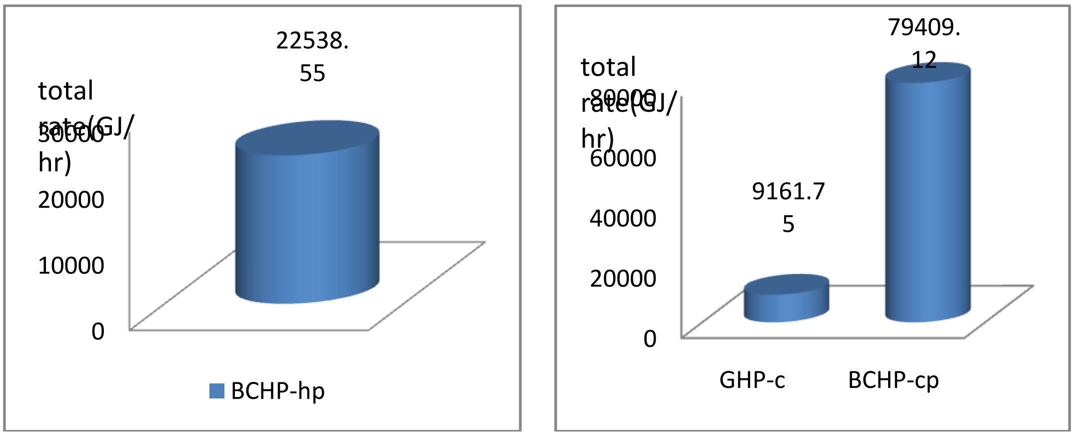


Figure 34. Cooling distribution network for minimum CO2 emissions.



Energy supply pattern in winter Energy supply pattern in summer

Figure 35. Energy supply pattern under CO2 emissions minimisation

In order to explore the trade-off in more detail, we perform several optimisation studies in order to generate a pareto-optimal curve. This is obtained by minimising the cost subject to an upper-bound constraint on the CO_2 emissions. Initially, no constraint is imposed and then subsequent optimisation problems employ progressively tighter constraints on the CO_2 emissions until the problem become infeasible or a sensible point is reached. A second series of points can be obtained by minimising the CO_2 emissions subject to a series of constraints on the cost. The results of these two sequences of optimisations are shown below. As can be seen, the cost increases steadily as the CO_2 emissions are reduced, but there appears to be a limit where further reductions become progressively more expensive. Clearly, understanding (or at least knowing) the nature of this curve is key to making informed decisions about the level to which CO_2 emissions can be reached (or is worth reaching). This ability to explore the cost implications of increasing decarbonisation leads into the next section on abatement costs for cities.

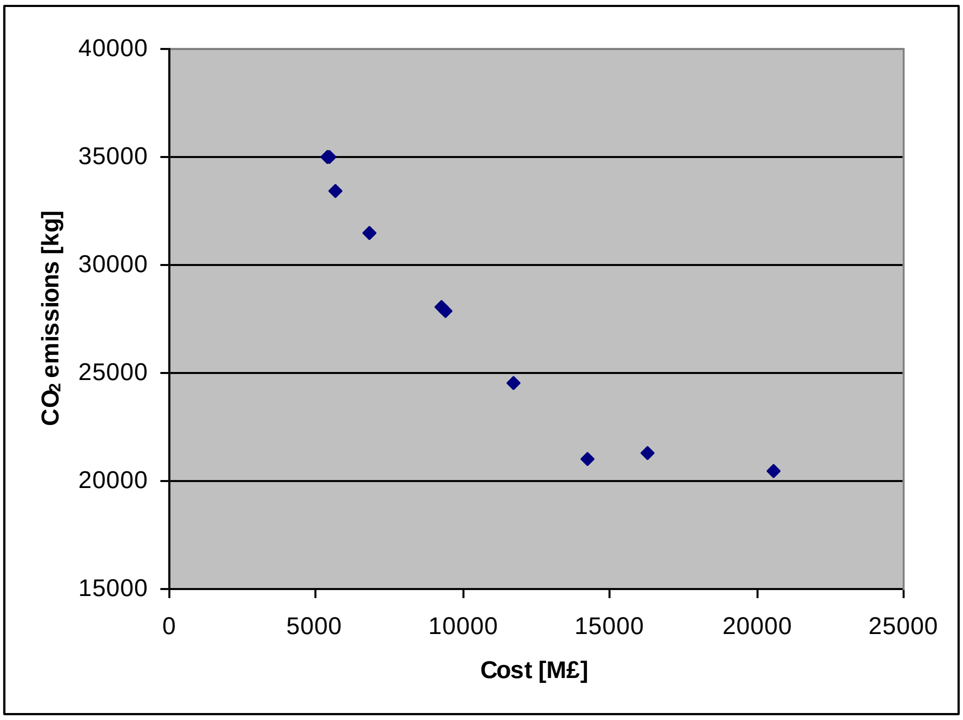


Figure 36. Pareto-optimal curve, comparing cost and CO2 emissions.

Marginal Abatement Cost Curves (MACCs) for Cities

The application of marginal abatement cost curves (MACCs) has become a standard method to illustrate the supply side economics of carbon abatement initiatives. MACCs already exist for plant level analyses as well as at country, regional and sectoral level. However, recent literature fails to provide an approach that takes the special conditions of cities into account. The approach developed in our work will provide a systems and network oriented bottom-up abatement cost curve model based on a case study of an eco-town in the United Kingdom.

Over the last decade, marginal abatement cost curves (MACCs) have become a common method of analysing the consequences of the Kyoto Protocol's economic impacts on national GHG reduction policies. Marginal abatement cost curves illustrate the estimated cost of abatement as a function of the emissions level. They are a valuable tool for energy modelling and environmental policy analysis because they provide an estimate of the cost to make incremental reductions from a given emissions level. More specifically, a MACC delivers the cost of reducing one additional unit of pollutant from a given emission level. Normally, every additional unit of emission reduction has an incrementally higher cost, leading to a characteristic convex shaped curve with increasingly positive slope.

The abatement cost curves for this analysis were developed by applying the SynCity RTN model. Creating an abatement cost curve requires two input values: (1) An amount of mitigated GHG emissions and (2) the related cost. This information is readily generated by performing successive SynCity runs with increasingly stringent carbon constraints.

Defining a Baseline – Applied Methodology

The emission and cost baselines are crucial for an appropriate analysis and later cost derivations because all calculations and visualisations are shown relative to this baseline. For our case study (where we consider the non-transport emissions), the emission baseline was developed by limiting the available technologies to business-as-usual gas boilers, electric heaters and grid electricity. Considering the two projection years 2020 and 2030 and

hence changing prices for electricity and related grid carbon intensities, the RTN model minimised the Total Costs assuming no technology changes i.e. boiler efficiency increases.
The abatement cost curves for the given eco town case study are illustrated in Figure 37. They show the total abatement cost in GBP in relation to the level of abatement. At first glance, two major differences become obvious. Firstly, the difference in the maximum abatement potential for the years 2020 and 2030 and, secondly the remarkably different shapes of the two curve groups.
For 2030, there was no attainable solution for emission reductions above 70% compared to the business-as-usual emission number created only by the application of boilers. In 2020, compared to the baseline emission amount, there was no abatement potential above 50%. This difference derives mainly from the different assumed carbon intensities for grid electricity at these two points in time.

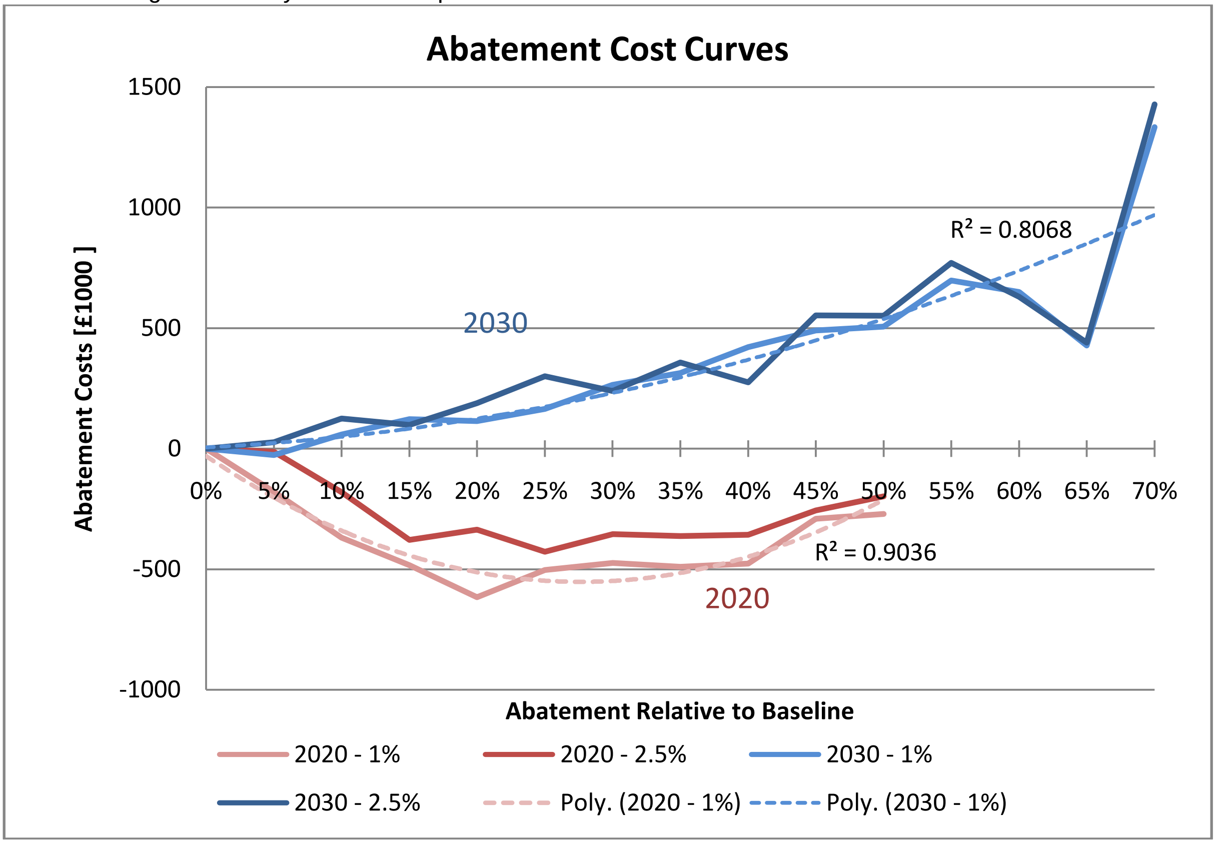


Figure 37. Abatement Costs Curves for 2020 and 2030

The interpretation of the abatement cost curve for the proposed eco town is as follows: 50% of carbon emission abatement in 2030 could be possible with expenditures of roughly £500,000 or 30% mitigation for approximately £260,000.

A particular feature of the optimisation is the significant drop at 65% carbon abatement in 2030. This drop derives from a change whereby a comparatively large, CHP unit after the 50% constraint is removed, resulting in a discrete, systemic change. Nevertheless in combination with the following graphs, the abatement cost curve for 2030 provides further insights.
The transitions in fuel types and conversion technologies are illustrated below. We see the substitution of gas by low carbon electricity imports as shown in Figure 38. It is also congruent with the simultaneous decrease of CHP usage and thus on-site electricity production.

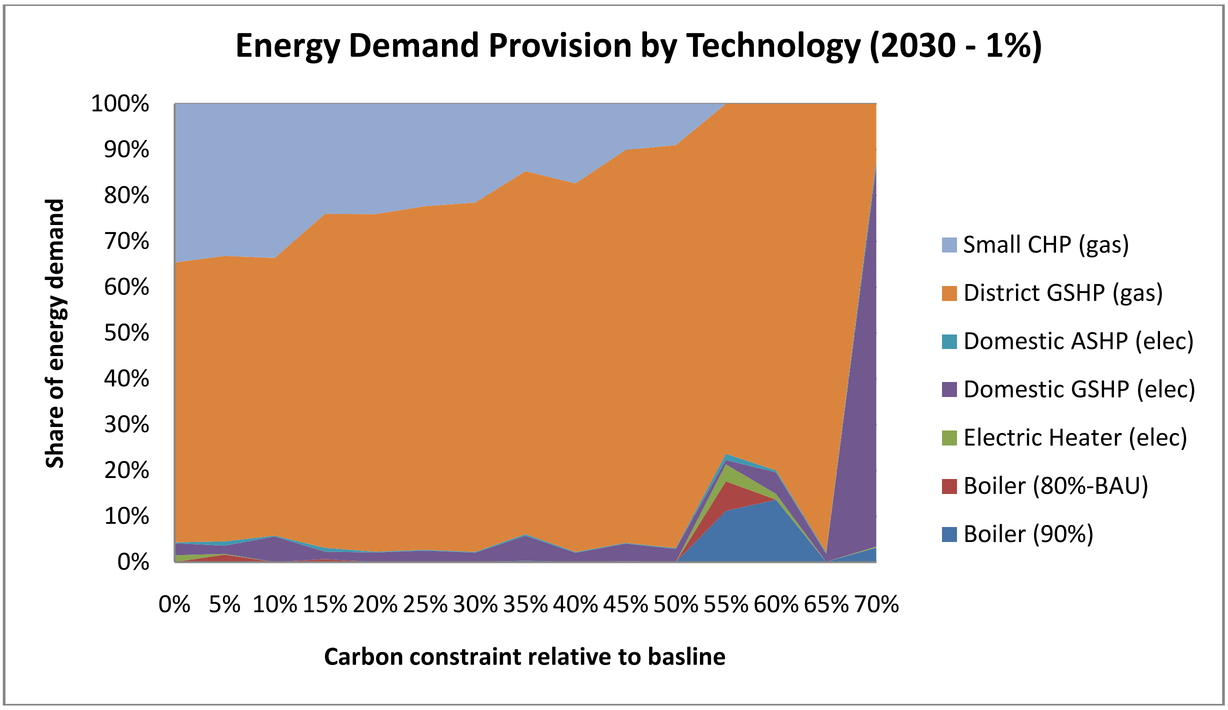


Figure 38. Technology Utilization: 2030 case

Taking the energy demand provision and the resource import chart into account leads to the conclusion that the emission reduction for 2030 is achieved by a substitution of on site produced electricity (via CHP) through imported (low carbon) grid electricity. This leads to the important insight that very low carbon cities are most economically achieved through interventions combining local energy demand reduction and decarbonisation of national energy systems; this is consistent with current UK strategy.

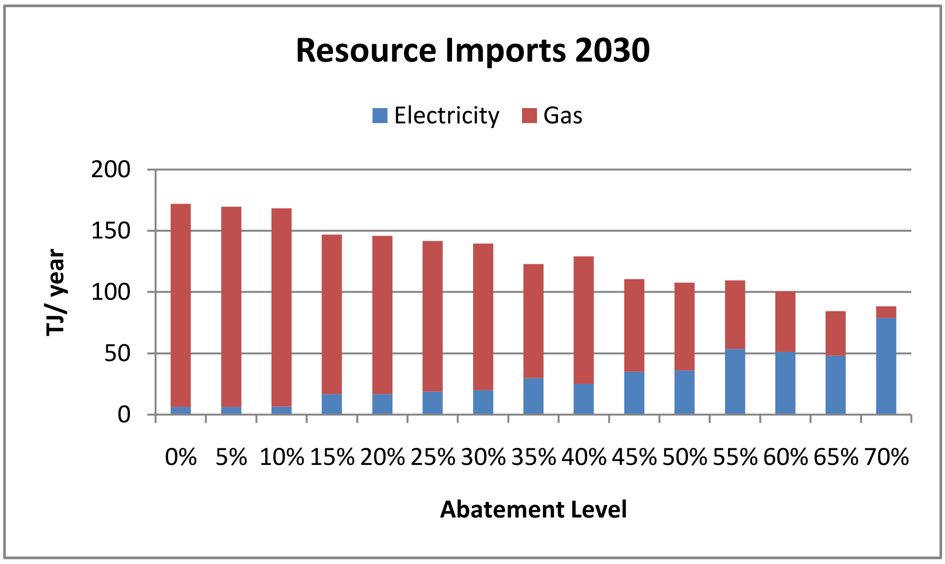


Figure 39. Resource Imports: 2030 case

Bearing in mind the only differences between the two analysed years were the electricity price and the grid electricity carbon intensity, the cost curve for 2020 delivers a significantly different picture compared to the curve for 2030.

The comparison of the abatement cost curve with the energy demand provision curve leads to the conclusion that there is still potential for an overall system optimisation – reducing Total Costs and confining the amount of Total

Carbon emissions at the same time. This effect can be observed in Figure 40 between the origin and the 20% emission constraint.

After the emission reduction rate of 20% there is no further energy system optimisation potential and the abatement costs increase. However they remain negative due to the achieved optimisation benefits in the first reduction steps.

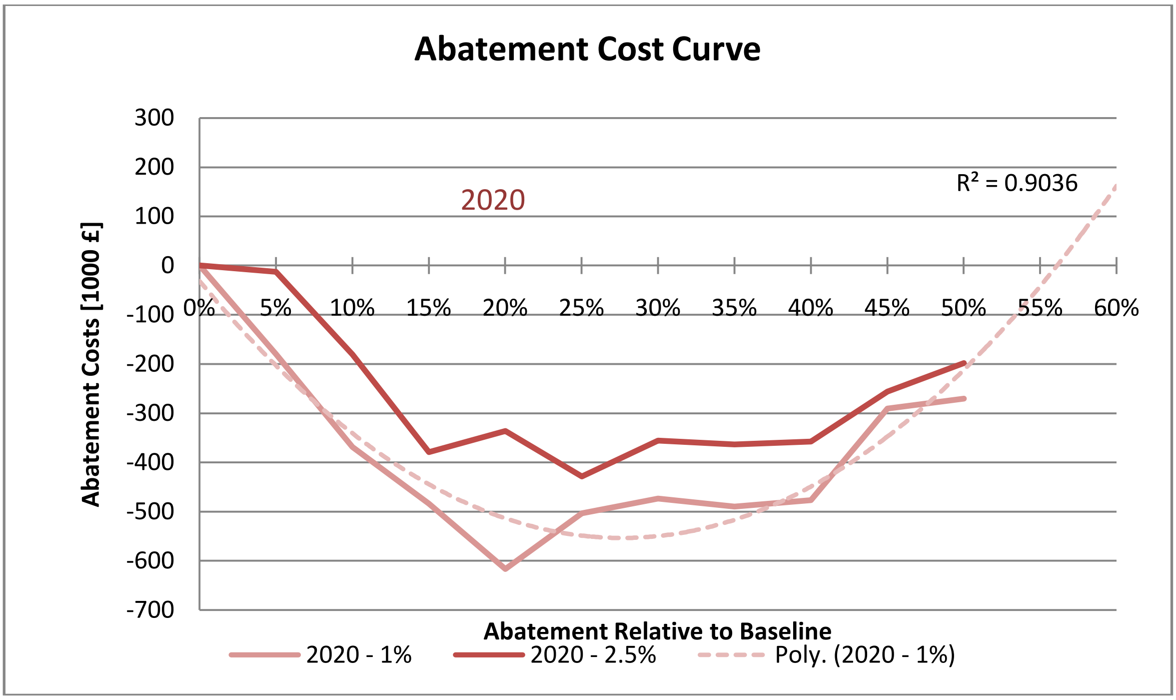


Figure 40. Abatement Cost Curve 2020

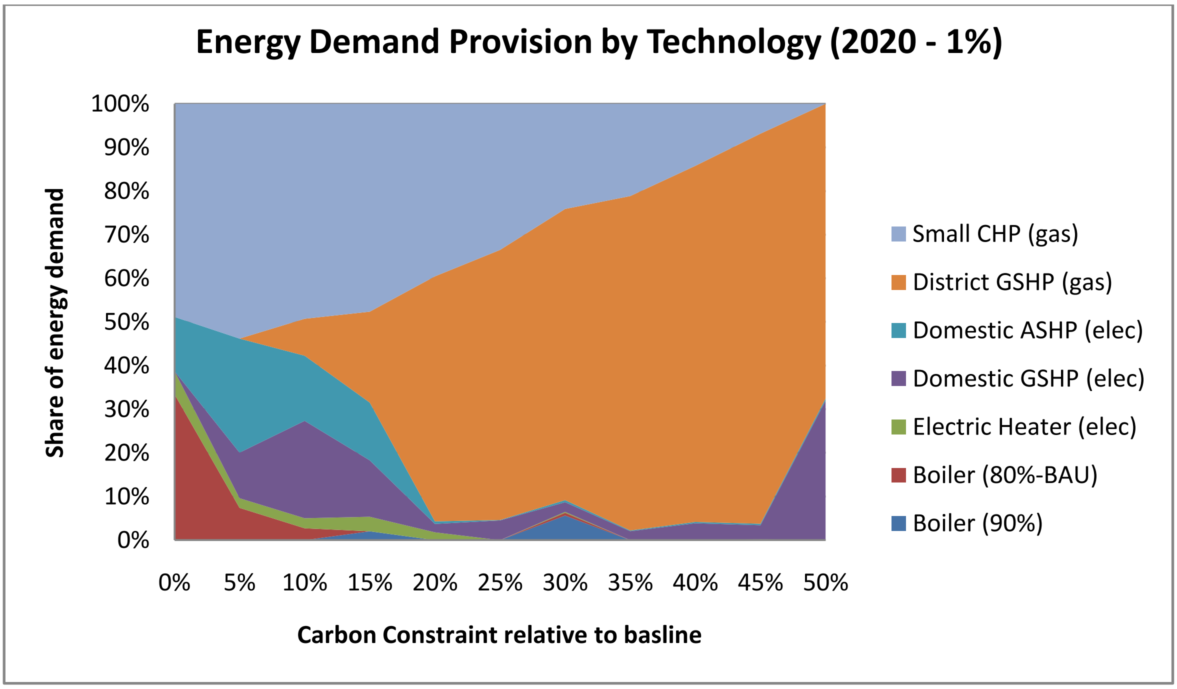


Figure 41. Technology Utilization: 2020 case

After the 20% emission reduction mark, the technology utilization is similar to that for 2030 as shown in Figure 41. Also similar to 2030 is the predominant energy supply by small CHPs and gas fired district GSHPs, with a decreasing tendency for CHPs and increasing utilization of GSHPs. After the turning point at 20% the increase in the 2020 abatement costs is also similar to the 2030 one. This is again due to the incremental substitution of gas by electricity.

Case Study – Developing a Low-Carbon Transition Plan for the Peanut District, Toronto

Toronto has been involved in urban policy development since the first international conference to discuss the dangers of GHG emissions, and today Toronto's Mayor Miller chairs the C40 group of cities. Nevertheless, the lack of pressures on availability of energy and land has resulted in a sprawling city, though Toronto is distinguished by clusters of high and low density throughout the city unrelated to distance from the centre. The City has put in place stringent emissions reduction targets to tackle this high energy consumption, and one of its key approaches to achieving this goal is to prioritise a primarily neighbourhood-based approach.

The city has strong policies in place to encourage and facilitate sector-specific GHG emissions reductions, in both conservation and renewable generation. However, the maximum achievable potential with these measures is not sufficient to allow Toronto to meet its emissions reductions goals. This project (undertaken by an MSc student, Mabel Fulford) has demonstrated that a holistic and integrated approach to energy planning at the community level can result in far greater savings than estimated using a sector-specific approach. Applying the SynCity framework has enabled a comprehensive assessment to be carried out on the energy systems of the Peanut District, and a number of conclusions can be drawn from its results.

Primarily among these are the significant gains achievable through the implementation of district heat networks, which were found to offer 20% reduction in cost under current conditions versus a case of simple technology replacement. This is a conclusion that could not have been reached in the absence of a systems based approach that considers the neighbourhood as a whole. The results of this analysis also demonstrate that it is both physically and economically feasible for the Peanut District to meet Toronto's emissions target of 80% below 1990 levels by 2050 using currently available technologies, although the total cost will depend heavily on factors such as the evolution of the carbon intensity of Ontario electricity, and suggest that ground source heat will be an essential source of heat to meet the needs imposed by the Toronto climate in the context of carbon constraints.

Figure 42. The Toronto "Peanut" District

Overall, this project indicates that the potential to design better urban energy systems by taking a systems approach is significant, and provides an example of how this can be achieved at the neighbourhood scale for energy systems in Toronto. This project drew on several major sources of data to build a model of the Peanut District, including:

- Statistics Canada 2006 Census in conjunction with GeoSearch 2006 (Statistics Canada, 2006)
- The Central Energy Use Database (CEUD) published by the Government of Canada (NRCan, 1990-2007)

- Residential Sector and Commercial Sector: Ontario Tables, data from the year 2007
- Ontario Ministry for Energy and Infrastructure (MEI): Heating and Cooling Guide (MEI, 2009)
- Mayor's Tower Renewal: Community Energy Plan (CEP) for Pilot Sites, commissioned by the City of Toronto and conducted by ARUP Canada Inc. (Arup, 2010)
- Tower Renewal Guidelines, created by a research group at the University of Toronto (Kesik and Saleff, 2009

A map of the district was created using Quantum GIS, an open source Geographic Information System software. The map is based on the Toronto Centreline data set which includes roads, rivers, administrative boundary.

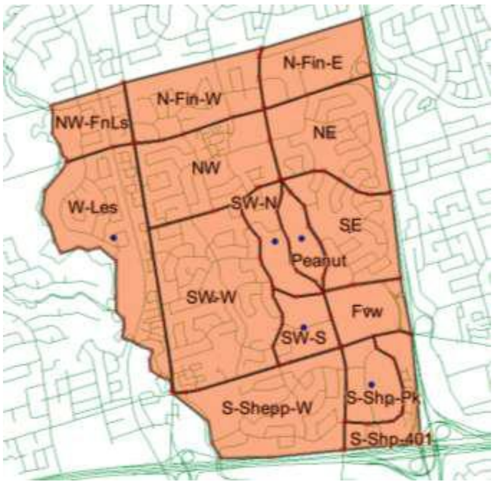


Figure 43. Spatial disaggregation of the study region

A variety of data sources were combined to obtain spatially-explicit energy demands. Residential buildings dominate the overall energy demand accounting for approximately 70%, and the importance of residential demands in most neighbourhood zones is far greater with most non-residential demands coming from a handful of facilities situated in just 3 zones. When viewed over the neighbourhood, it becomes clear that high rise households play a major role in overall residential demands despite their small land footprint, and will significantly affect technology choices in each zone even where zone demands are similar in magnitude. Total demands per zone are shown in Table 2, along with an illustration of the contribution of types of users.

		Heat	Hot Water	Electricity	Total	Commercial	HR Residential Share
Zone 'id'	Description	GJ/yr				% of Total	% of Residential
1	NW	140,007	24,938	64,346	229,292	10%	35%
2	NE	75,486	12,041	32,513	120,041	8%	37%
3	SE	110,663	18,477	52,399	181,539	4%	57%
4	SW-W	125,223	18,896	49,141	193,260	18%	0%
5	SW-N	83,116	14,556	41,369	139,041	0%	68%
6	SW-S	72,660	12,664	40,284	125,608	7%	74%
7	S-Shepp-W	82,713	12,958	34,755	130,426	12%	26%
8	S-Shepp-Pkwy	89,951	16,062	61,160	167,173	17%	93%
9	S-Shepp-401	71,859	12,737	38,162	122,757	4%	70%
10	W-Les	82,959	13,832	28,147	124,939	8%	0%
11	NW-FinLes	23,479	4,393	7,054	34,926	0%	0%
12	N-Fin-W	60,753	10,732	28,822	100,307	15%	31%
13	N-Fin-E	135,412	23,240	146,906	305,558	73%	100%
14	Fairview	98,484	14,371	129,239	242,093	100%	-
15	Peanut	39,844	5,846	52,224	97,915	100%	-
Whole Peanut District		**1,292,609**	**215,744**	**806,521**	**2,314,875**	**31%**	**47%**

Table 2. Energy demands by zone

The assessment of a series of scenarios has provided several points of learning that can be applied in the Peanut District. The first is that, under almost any conditions, the replacement of current technologies with new units at the highest available efficiency, even if the current units are not near the end of their lifetime, is overwhelmingly positive from a cost perspective for individual homeowners or building managers. However, just as is concluded by the Mayor's Tower Renewal for large, aging concrete towers, in the context of widespread replacement of current energy systems it is wise to assess options that do not simply extend the status quo with marginal improvements, but that represent all available alternatives. The significant legacy aspects of this neighbourhood provide a strong motivation to address energy use and, similarly to the MTR buildings, present a particular opportunity to assess the energy systems as a whole –building stock is fairly uniform across the neighbourhood and is reaching a condition suitable for refurbishment or renewal, and the physical layout of the neighbourhood opens up many options for integration of different energy systems. The application of the Peanut District model reveals an overwhelming potential for district-wide solutions, which overshadows the impact of choosing between different types of technologies on the building scale. A district heat network serving the majority of end-users in the area, supplied by several centralised CHP units, and supplemented by some point of use technologies to manage variations in demand, represents the lowest cost solution for the current needs of the neighbourhood without regard for emissions. However, as a technology that does form part of the lowest cost solution under the current conditions, GSHP becomes essential in the long term as the only technology that is able to satisfy the heat demands imposed by the Canadian climate with a renewable and sustainable urban resource. The technology solutions at the sharp ends of this time period are in fact highly complementary, and provide a strong argument for the Peanut District to develop a CEP outlining the creation of district heat networks, that commence around clusters of high rise buildings before extending across the whole community, and which are initially supplied by a small number of CHP units, gradually evolving to accommodate higher contributions of renewable heat from GSHP. The figures below show the CO_2 emissions and costs associated with different system designs.

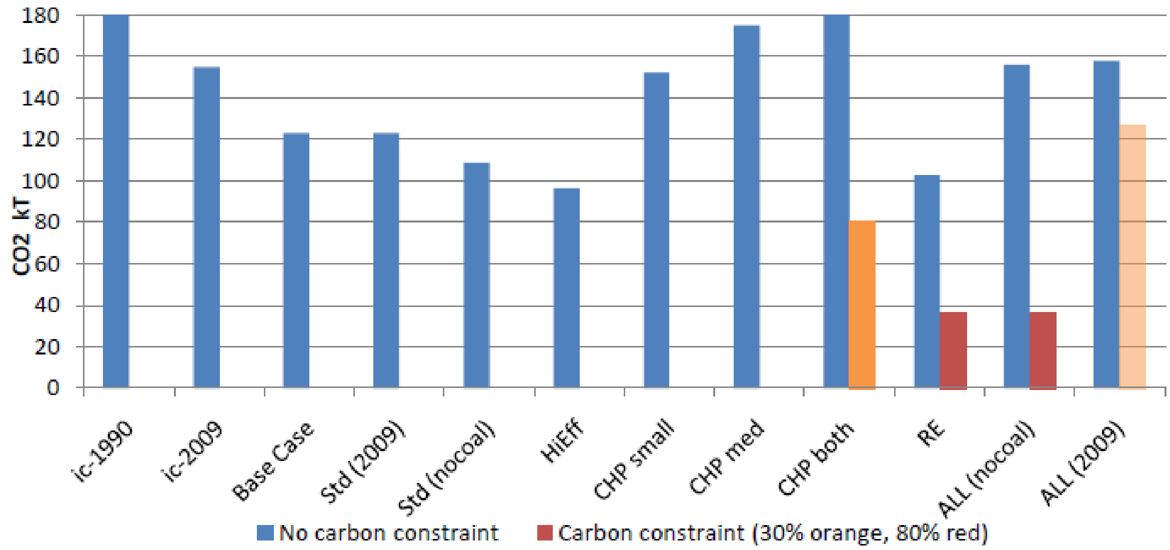


Figure 44: Comparison of carbon emissions for various technology scenarios for Toronto's Peanut District.

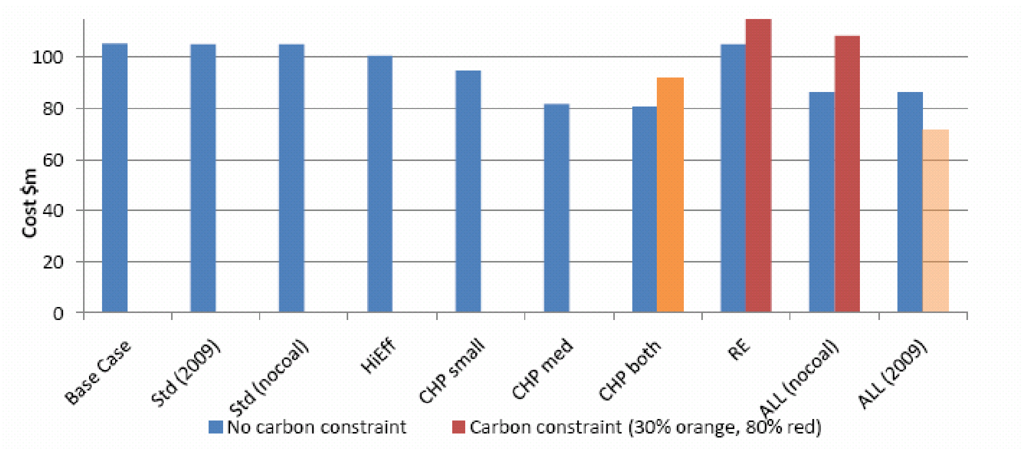


Figure 45: Comparison of system costs for various technology scenarios for Toronto's Peanut District.

Smart neighbourhood operation

In this work, we move from design to operation, reflecting some of the most recent work in the programme. Here we consider a number of buildings connected by a microgrid encompassing distributed energy resources and automation systems. This idea is based on the concept of the smart home which in turn originated from the concept of home automation, which provides some common benefits to the end users, which include lower energy costs, provision of comfort and security and provision of home-based health care and assistance to elderly or disabled users.

The smart homes power consumption scheduling problem is formed as a mixed integer linear programming model. The daily power consumption tasks are scheduled based on their given operation time window (earliest starting time and latest ending time), and the objective is to minimize the daily power cost and shave the power consumption peak. It assumes the smart neighbourhood has its own microgrid and some decentralized resources (such as wind generator, CHP generator, boiler, thermal storage and electrical storage) to provide the basic electricity and also it has a grid connection to obtain electricity during peak hours or sell electricity to the grid when there is surplus electricity generation. Since this model only provides the optimal scheduling for one day, equipment capacity selection is not considered and all the equipment capacities are given. The electricity price from the grid is given and may vary according to time of day. The model also assumes the weather forecast can provide 24 hour wind speed data.

The case study neighbourhood has 30 homes with the following energy supplies:

- one CHP generator with a capacity of 40kW$_e$ its electrical efficiency is 35%, heat to power ratio is 1.3, and natural gas cost is 2.7p/kWh;
- one wind farm with a capacity of 10kW$_e$ and a maintenance cost of 0.5p/kWh$_e$;
- one boiler with capacity of 80kW$_{th}$ and natural gas cost is 2.7p/kWh;
- one electrical storage with a capacity of 10kW$_e$; the charge/discharge efficiency is 95%, discharge limit and charge limit are both 10kW$_e$, and the maintenance cost is 0.5p/kWh$_e$;
- one thermal storage with a capacity of 20kW$_{th}$; the charge/discharge efficiency is 98%, discharge limit and charge limit are both 20kW$_{th}$, and the maintenance cost is 0.1p/kWh$_{th}$;
- a grid connection (allowing import and export of electricity when operating parallel to the grid), the electricity price at different times is given in Table 3 and when electricity is sold to the grid, it is 1p/kWh$_e$;

Each time interval is half an hour, so there are a total of 48 time intervals. The total heat demand profile is generated for a building with floor area of 2500m^2 on a sample winter day. For the electricity demand, each home has 12 basic tasks that consume electricity as shown in Table 4. These tasks are available to be scheduled according to the given earliest starting time, latest finishing time, their respective processing time and power requirements.
In this case study, there are 10 identical wind generators, with an efficiency of 47%. The blade diameter is 1.6m and the wind speed is generated from a Weibull distribution with a mean velocity of 7m/s. The cut-in and cut-out wind speeds are respectively 5m/s and 25m/s, and the nominal wind speed is 12m/s. The wind generators do not produce any power when the wind speed is under the cut-in speed or above the cut-out speed. When the wind speed is above the nominal wind speed, the power output is at the maximum output, which is equal to the output produced at the nominal wind speed.

Results with earliest starting time

The starting time of the case study is from 8am and the ending time is 8am the next morning. The earliest case means all the domestic electricity appliances are turned on at their given earliest starting time, i.e. without any load scheduling. The optimal heat balance resulting from this case is shown in Figure 46 and the optimal electricity balance is shown in

Figure 47. The electrical storage is used to store electricity when there is excess electricity; it is mainly for utilizing the wind generator output more efficiently. Excess electricity has to be sold to the utility grid when the electrical storage capacity is exceeded. With the earliest starting time schedule, the peak hours are mainly during the evening when people are back from work. During this time, about 48% of the total electricity is imported from the utility grid. The total cost is £140.0.

Results with time window

When a time window is allowed, the domestic tasks are scheduled in order to minimize the total electricity cost. The optimal heat balance is shown in Figure 48 and the optimal electricity balance is shown in Figure 49. Thermal storage is not used in this case. There are only two peak periods: early in the morning and in the evening. The other time periods have flat electricity consumption. Only 12% of the total electricity is bought from the utility grid, electricity being mainly provided by the local distributed resources, and there is no electricity sold back to the utility grid. The total cost is £118.2, which is 15.5% lower than the earliest starting time case.

Time period (hour)	Electricity price (£/kWh)
8-13	0.08
13-16	0.11
16-21	0.08
21-8	0.05

Table 3. Electricity tariff

	Task	Power (kW)	Earliest starting time (hour)	latest Finishing time (hour)	Duration (hour)
1	Dish Washer	1	9	17	3
2	Washing machine	1	9	12	1.5
3	Spin Dryer	3	13	18	1
4	Cooker Hob	3	8	9	0.5
5	Cooker Oven	5	18	19	0.5
6	Cooker Microwave	1.7	8	9	0.5
7	Interior lighting	0.84	18	24	6
8	Laptop	0.1	18	24	2
9	Desktop	0.3	18	24	3
10	Vacuum cleaner	1.2	9	17	0.5
11	Fridge	0.3	0	24	24
12	Electrical car	3.5	18	8	3

Table 4. Task electricity consumption profiles

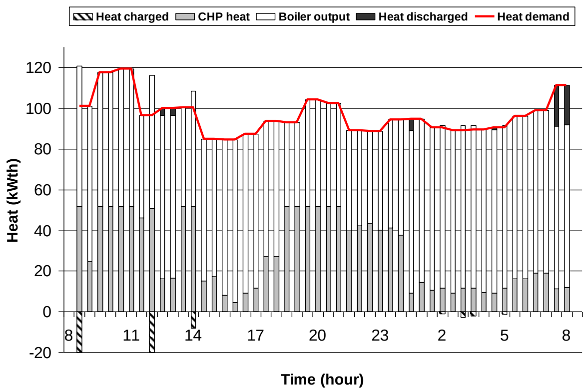


Figure 46. Heat balance with the earliest starting time

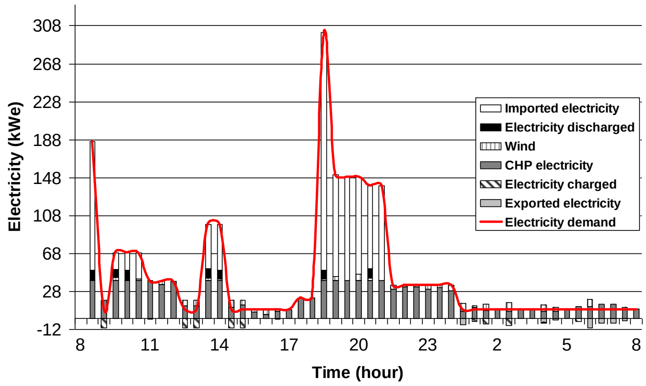


Figure 47. Electricity balance with the earliest starting time

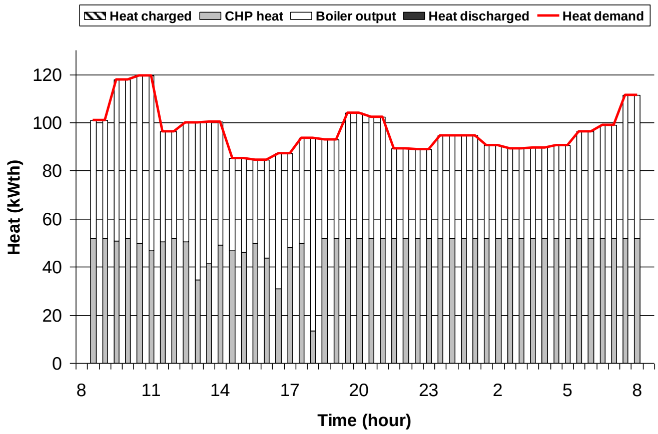


Figure 48. Heat balance with time window

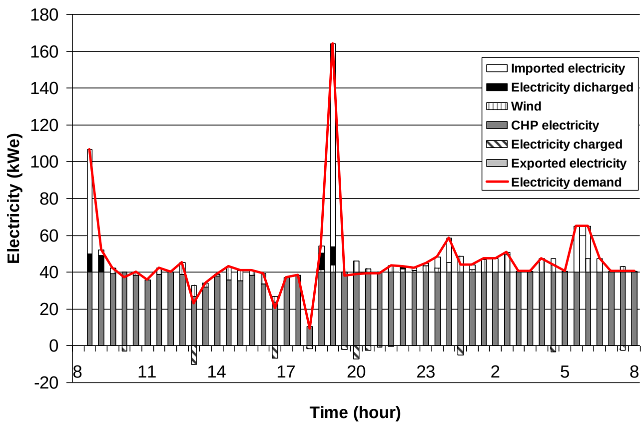


Figure 49. Electricity balance with time window

In the case study, twelve domestic tasks from thirty homes are scheduled. Compared with the case where the tasks all start at their earliest possible starting time, the electricity consumption peak was decreased from 290kW to 165kW and the electricity consumption pattern became flatter. This peak shaving has the benefit of releasing the burden on the central grid and reducing the expense of up-grading the current grid structure to fulfill increasing energy demand. The peak shaving also depends on the family living habits: for instance, they may prefer doing the washing during night time and would specify their own time window for the task. On the other hand, when the domestic task scheduling is implemented in real life, it could also affect people's behaviour.

Given the fixed heat demand profile used in these case studies, scheduling the tasks results in a more balanced heat supply than the earliest starting time case. This can be seen in Figure 48, which shows that the CHP unit is providing more heat more steadily than in the earliest starting time case. In addition, the thermal storage was not used. The tasks shown are assumed to have constant power consumption over the processing time but this is not always realistic: e.g. washing machines have different power consumption during different stages of each program. Future scheduling models will need to account for tasks with time-varying power consumption.

The smart homes energy consumption scheduling problem is formulated as a mixed integer linear programming model. According to the case study for a winter day, it could provide 15.5% savings compared with the earliest starting time case (our current living habit). With the objective function, the tasks can be scheduled to coincide with the cheapest electricity price while keeping their operation within the desired time window. There are further benefits more when power is supplied by the wind generator. The power output from the wind generator is not constant and varies from hour to hour according to the weather conditions and other constraints. But when a weather forecast can be used to predict the power output during the next 24 hours, or even longer, the domestic tasks can be scheduled to use the output of the wind generators when it is available, providing further savings for the customers. The scheduling formulation also increases the asset utilization, e.g. in the case study, the CHP generator was be used more efficiently and became the main supplier of electricity and heat.
In the area of Smart Grids, it is expected that there will be two-way communication between the power supplier and the customers. The power will be distributed according to the demand and supply. Traditional methods provide the customers only peak price hours while the Smart Grid could provide real-time electricity pricing. The process of price recalculating is similar to real-time traffic monitoring, aiming for a balance between supply and demand. This model considers the problem from the point of view of the customers, with a fixed electricity price profile. In the future, it might be possible to include this model as part of a full Smart Grid model where the electricity price is determined as part of the optimization, along with the scheduling of tasks.

Urban Energy System Retrofit

Existing cities provide the challenge, and opportunity, of retrofitting energy systems in an integrated and improved manner. Mathematical programming provides a suitably systematic decision making tool-kit for decision makers. Optimization and operations research have been applied to many domains, yet research on retrofitting of urban energy systems has been limited. Previous research and applications have largely focused on heat exchanger networks and other processes in industrial complexes. However, given the potential of optimization to provide a novel view of retrofit and to quantitatively analyse the structure of retrofit systems, it was thought appropriate to apply the above methodologies to this problem.

The purposes of this strand of the BP-Imperial urban energy systems project are threefold: to analyse the potential of modelling and optimization, to provide estimates of the potential benefits, and to describe means and business models to achieve retrofit of existing cities' energy systems at the large scale. With these end-goals in mind the system of retrofitting buildings, in particular, has been systematically reduced to its elemental processes. The supply chain of retrofitting buildings can involve anywhere between one to twenty sets of decision makers, largely on account of the building tenure and scale of retrofit/regeneration. The typical sets of decision makers are as follows:

- Building owner
- Project manager
- Financer
- Designer
- Technology supplier and manufacturer
- Installer
- Building occupant
- Other (insurers, estate agents, special interest groups, etc.)

Given the somewhat diverse and fragmented sets of actors in retrofit, the processes under study have had to focus on what were thought the three most important processes: financing retrofit, planning retrofit actions, and organizing the logistics of retrofit. The appropriate methodology for studying these processes was first assessed.

Initially, a review of urban energy systems modelling found previous optimization applied to retrofit, beyond those for specific industrial technologies, was primarily at the building or neighbourhood level. Early results were presented at an international workshop. Typical objective functions to be minimised conflated the capital, installation, and operational costs together. Over the last decade however, research has continued to become more sophisticated, and this research has built on lessons learned from previous work. The results of this review have been accepted for publication as a journal article.

During the course of this review the various trade journals, conferences, and seminars provided evidence of the potential benefits of retrofits. These benefits have been described in an upcoming book chapter. Advantages from individual technologies accrue largely on account of improved control of space conditioning and electrical demand in buildings. Advantages from considering more than one building retrofit at a time allow for economies of scale for supply technologies, increased leverage for raising finance, and quantitative management of retrofit labour.

Following this review of methods and benefits, the lessons and insights from previous work were applied to the processes of financing, planning, and organizing retrofit. The end-products of these three related research areas are now described.

Financing UES Retrofit

A typical development appraisal finance model was built following extensive interviews with property developers, institutional investors, estate agents and consultants. The process of financing a retrofit was then divided into key activities. The decision variables of interest are the finance available from a set of financers and the arrangement of the fees associated with each type of finance. Given that there are three primary types of building tenure (owner occupied, privately rented, or rented from a public landlord) there are different financial constraints to each type of building retrofit. The typical financers are shown in Figure 50Figure 50.

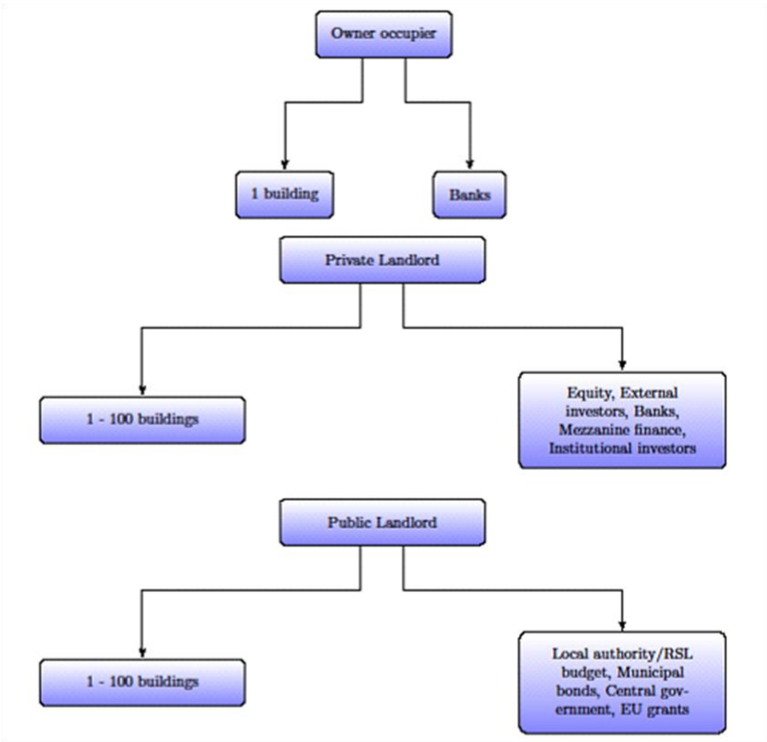


Figure 50. Typical agents involved in the financing of building retrofit, by tenure.

Note: RSL denotes registered social landlord.

A novel optimization model was built to include such constraints and provide a quantitative overview of the underlying activities. A case study, as accepted and submitted for publication as a conference paper, considered a small neighbourhood of London, specifically 205 terraced houses which were built by use of traditional red brick solid walls. As of 2012 the houses consist of 100 owner occupied houses, 59 privately rented houses, and 46 publically rented houses. The local council in this area of London has introduced a climate change mitigation target for 2020 such that a 40% reduction of 2005 levels of GHG emissions is aimed for. Energy efficient refurbishment of existing housing stock is a key strategy towards meeting this target.

The arrangement of finance was optimized for the energy efficient retrofit of the privately rented housing stock, using two objective functions – that of minimizing the total costs of financer (i.e. costs of arrangement fees, interest margins, etc.) and that of maximising the financing costs. The results are shown in Figure 51.

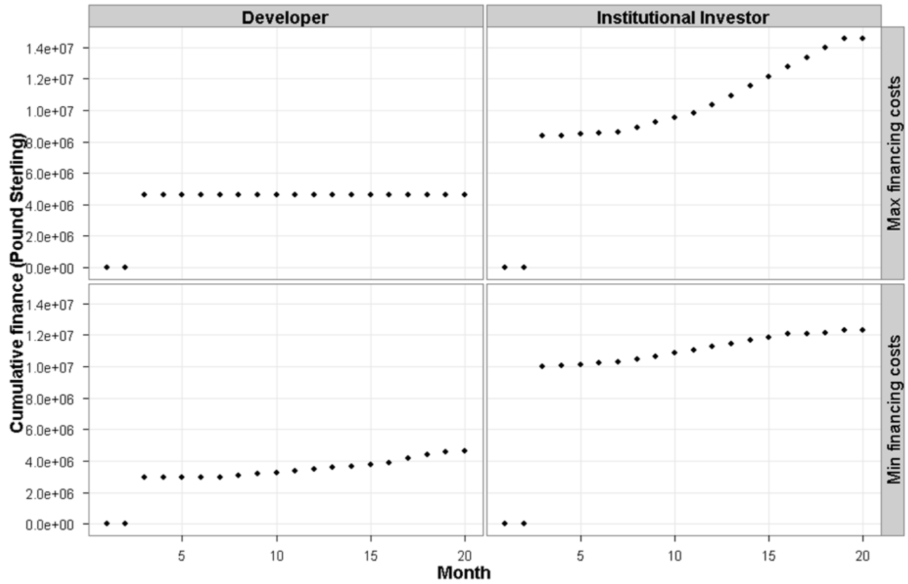


Figure 51. Private rented retrofit case study:

Finance provided by financer, month and amount, for both objective functions.

The results of the financial model were then fed into the RTN framework, with a modification such that existing technologies and demands could be included. Figure 52 illustrates the effect of financial constraints due to tenure on the rates of retrofit technology uptake (when the clear goal is minimization of greenhouse gas emissions).

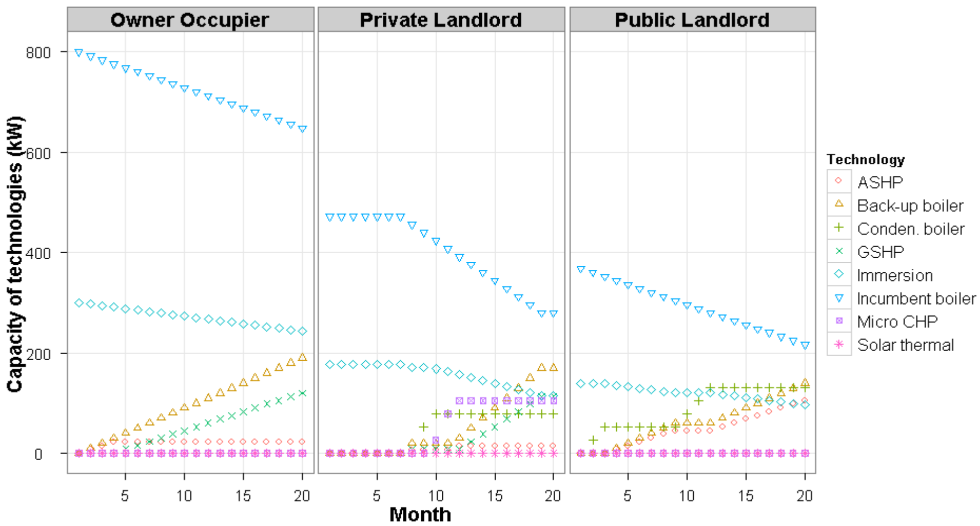


Figure 52. Private rented retrofit case study: Capacity changes by tenure.

UES Demand Side Strategies

The RTN framework was slightly modified to include retrofit interventions, as shown in Figure 52 above. A case study was undertaken, and the evolution of the model and study was presented in two conference papers during

2011. The RTN retrofit optimization was applied to the London borough of Haringey (see Figure 53), a conurbation with 19 administrative divisions (wards). The model has been calibrated to the ward of Seven Sisters, an agg[illegible]ses.

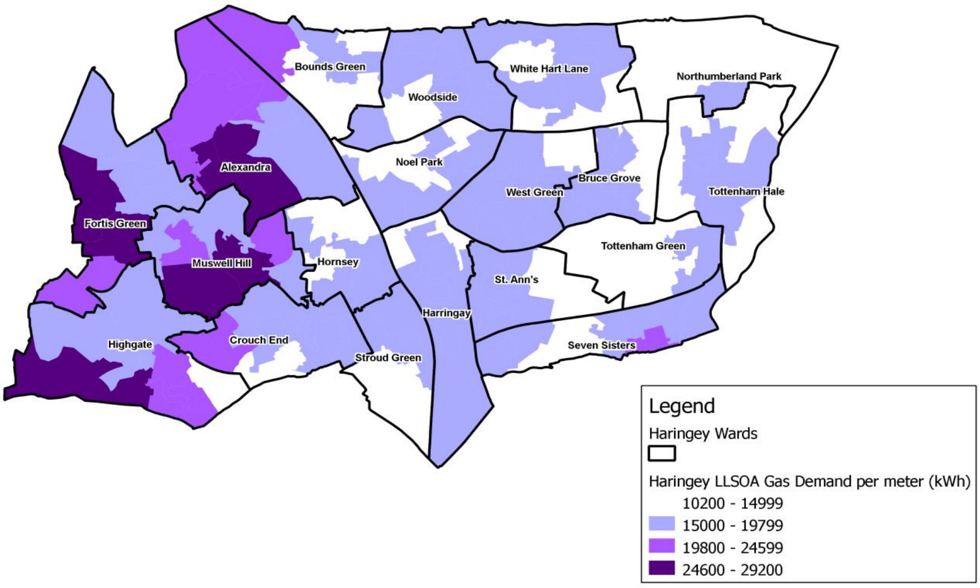


Figure 53. GIS projection of The London Borough of Haringey showing 2008 gas demand

The objective of the optimization was to plan the best schedule of retrofit installations between 2010 and 2050, based on greenhouse gas emission constraints. The effect of the resultant retrofit interventions on heating demand is shown in **Figure 54**. It can be seen that, with the caveats of assuming proper installation/commissioning and no rebound effects, heating demand is dramatically reduced once the demand side retrofit measures are chosen and installed.

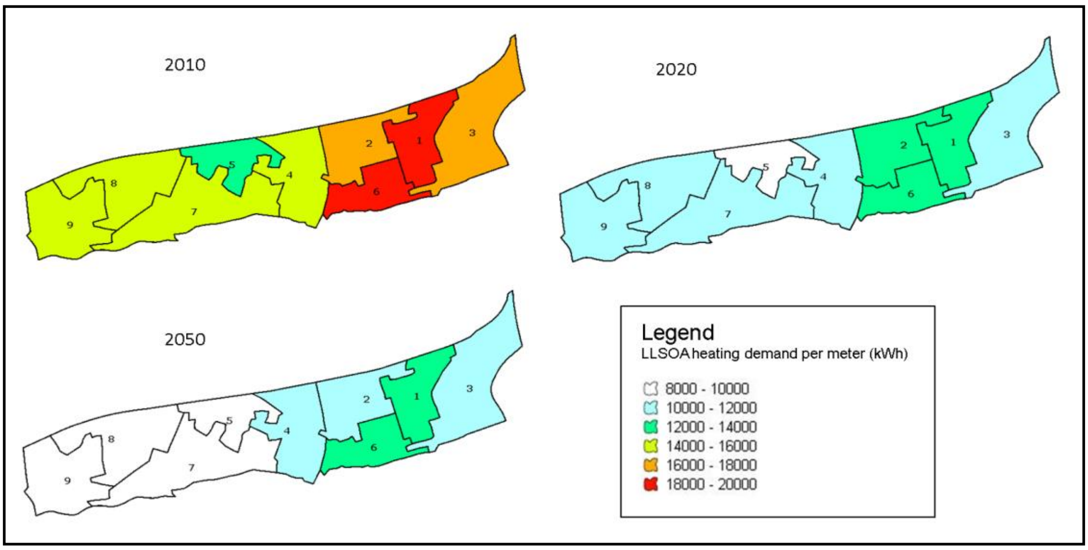


Figure 54. Evolution of heat demand in the Seven Sisters ward in London, for 2010, 2020 and 2050 in the 50% GHG emissions reduction scenario

The Supply Chain of UES Retrofit

An outbound logistics optimization model of the retrofit supply chain was built for the purpose of assessing the labour training, inventory levels, and learning rates of installers. This is thought novel. It was applied to a case study of a smart meter rollout for London between 2014 and 2019. Over one million smart meters are required to be installed by energy suppliers in this scenario, based upon the national mandate that all domestic homes in Great Britain will have a smart meter installed by 2019. The supply chain is shown in Figure 55. Smart meter supply chain. The decision variables in this optimization are the number of installers to be trained, the inventory levels of smart meters, and the timing and quantity of smart meter installations. The objective functions offered are the minimization of total costs, and the minimization of the total time taken for the installations. This study is currently due for submission as a journal article, and is thought useful as a framework that may be applied to the organization of the supply chain for many other retrofit technologies.

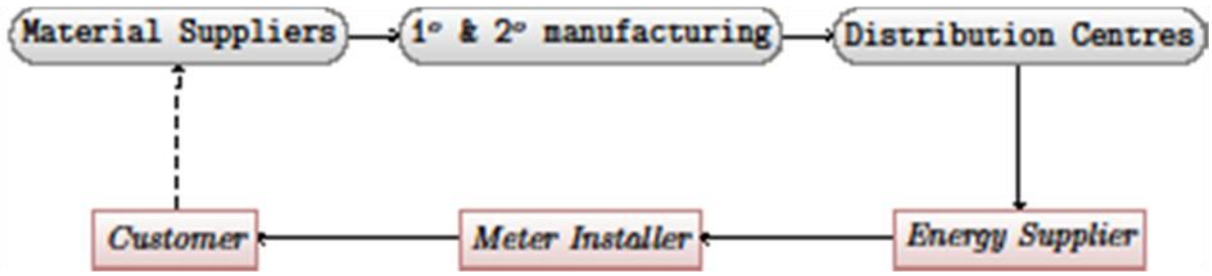


Figure 55. Smart meter supply chain

The three primary processes of importance in a system representing building retrofits at the large scale have been analysed in the form of mathematical modelling decision tools, as above. Results indicate there are at least two benefits to these models, firstly that the structure of the underlying activities may be made more transparent (e.g. the installation times of smart meter installers is not currently robustly measured by energy suppliers), and secondly that planning and integration of retrofit measures can provide real savings in terms of fuel and power demand and cost.

The BP-Imperial project has supported the development of robust modelling of retrofitting urban energy systems. It is expected that both academic and private research into systematic analyses of retrofitting urban energy systems will continue into the future, with optimization being used for many applications in the future as retrofit decision makers discover the usefulness of such methods.

6. Consumers and Business Model workstreams

In addition to the engineering-based programme, we have two complementary, business-oriented workstreams. One seeks to understand how and why consumers may adopt new energy efficient innovations and the other explores how new business models may arise out of the need to decouple value generation and resource consumption, and asks who the main agents of change might be in delivering new urban energy systems.

Consumers and innovation adoption

This workstream consists of three case studies. Initially, we built a conceptual framework and conducted an analysis of energy consumption in relation to household lifestyles, using the British Household Panel Survey (BHPS). We then started case studies: green tariffs, the Toyota Prius, and energy-sustainable domestic technologies (with Southern Housing Group - SHG). Since the last Annual Report, we have completed the third case study.

This case has explored: (1) how residents use and manage domestic energy-sustainable technologies, and (2) how policy affects professional and organizational practices. Between 2010 and 2012, we conducted 24 (8 x 3 stages) interviews with residents in a housing development in South East London, and 21 interviews with professionals who worked for and with SHG, such architects, contractors and Council sustainable officers. We have found that there are *tensions* between the way in which policy assumes residents to use recommended technologies and the way the residents actually use them in their everyday life. Similarly, we have identified diverse professional actors mobilise (and sometimes compromise) technologies to meet competing work priorities and also to comply with policy demands. In both cases, intended and expected sustainable effects are not necessarily achieved.

Overall, the work of this workstream will deepen our understanding of how users of sustainable technologies and services (both individual consumers and organizational professionals) perceive and experience them and how likely policy targets may be (or may not be) achieved. This has led us to make implications for policy, management and marketing.

We have published several journal articles:

- Ozaki, Shaw and Dodgson (2013, forthcoming) 'The co-production of "sustainability": Negotiated practices and the Prius', *Science, Technology, and Human Values*. (Toyota Prius)
- Ozaki and Sevastyanova (2011) 'Going hybrid: An analysis of consumer purchase motivations', *Energy Policy*, 39, 2217-2227. (Toyota Prius)
- Ozaki (2011) 'Green electricity tariffs: Why do consumers adopt?', *European Business Review*, March-April 2011, 10-13. (Green tariffs)
- Ozaki (2011) 'Adopting sustainable innovation: What makes consumers sign up to green electricity?', *Business Strategy and the Environment*, 20(1), 1-17. (Green tariffs)
- Ozaki and Dodgson (2010) 'Adopting and consuming innovation', *Prometheus: Critical Studies in Innovation*, 28(4), 1-16. (Conceptual framework)

Further three papers on the SHG case study are in the pipeline:

- Shaw and Ozaki, 'Performing government policy: making social housing development', submitted to *Organization Studies*. (SHG)
- Ozaki and Shaw 'Domestic 'sustainable' technology use: tensions between governing and performing practice', to be presented at the International Sociological Association's Environment and Society Research Committee in August 2012 and to be submitted to a journal in 2012. (SHG)
- Shaw and Ozaki, 'Sustainable technologies and practices (provisional)', to be written in 2012. (SHG)

7. Dissemination/third party engagement strategy

Outreach activities

The team had a busy year promoting its research at a variety of conferences and events. This included presentations at the major energy systems conference ECOS 2010, the waste-to-energy conference WasteEng 2010, an Agent Technologies in Energy Systems workshop in Toronto, and organizing a workshop at the Next Generation Infrastructures conference in China. Keynote speeches were also presented at the Gordon Conference for Industrial Ecology and the Communities for Advanced Distributed Energy Resources annual event in the United States. James Keirstead also spent one month as a visiting researcher with the Institute for Industrial Science, University of Tokyo, learning more about their extensive work in the area of building energy systems monitoring.

Within college, the project had a high profile through a two-week MSc module and the supervision of eight MSc project theses. We also linked with the business school to supervise a six-month MBA project on the commercial opportunities for SynCity.

5.1 Collaborations

We have established a structured approach to collaborations. Key features of this are:

- A tiered approach with 3 tiers:
  - Tier 1 "strategic collaborators" would involve joint work across most or all of the workstreams; we expect a maximum of about 7 of these and need to ensure that there is a relationship manager on each side
  - Tier 2 collaborators would involve joint work across more than one workstream
  - Tier 3 collaborators would involve joint work in one workstream

- A set of criteria to be applied when evaluating a potential collaboration which, in priority order, are:
  i. Access to data/geographical advantages
  ii. Implementation/piloting capacity
  iii. Complementary expertise
  iv. Similar expertise

Our key collaborations are:

Columbia University [publication]

The first objective of this collaboration was a three-way comparative study of London, New York and Shanghai. The initial focus is a short study on the potential for energy-saving measures and technologies in these three cities, and comparing and contrasting the energy strategies and associated initiatives of the three cities. The London study focuses on the potential for combined heat and power and the New York study on demand side and energy saving measures. The Shanghai study has not yet been finalised. The product will be a report on climate change preparedness of various cities as well as general comments on urban mitigation potentials with a policy twist to it.

Website: http://energy.sipa.columbia.edu/urbanenergy.htm

National Energy Center for Sustainable Communities/Global Energy Network

This is a collaboration between the GTI, DOE, San Diego State University, UCSD, the California Energy Commission and others which aims to apply a holistic approach to the design of sustainable cities. They are interesting because they offer an implementation and data collection opportunity in the new development of Chula Vista, a new town outside San Diego (see http://www.necsc.us/site.php). A proposal was prepared together with the CV team for funding from the CEC PIER programme.

The technology, science and project activities proposed under this program will focus on whole building and community systems integration (Project 1), municipal guidelines and standards for community-scale energy efficiency and carbon reduction (Project 2), and market adoption of advanced energy-efficient and renewable energy technologies (Project 3). The proposal was not successful, but has led to a new public-private partnership for sustainable community development projects that we hope to collaborate with.

Tsinghua University

There are active collaborations with the wider energy community via the Energy Futures Lab (e.g. clean coal polygeneration; hydrogen infrastructure; Chinese energy roadmap) and Centre for Transport Studies. We have been in discussions with the Tsinghua Clean Energy Centre regarding working with the UES team on a Chinese city study, e.g. Langfang.

Shanghai Tongji University

Through the Ecocit Research Network (www.ecocit.org) we have established a link with the group of Prof Long Weiding at the Institute of Sustainability. We hosted have an academic visitor from the group, Mr Liang Hao, who applied SynCity to the design of Lingang New City – a low carbon demonstration city in the port area of Shanghai. We are now planning a second case study.

Figure 56. Lingang New City

Arup/C40 cities partnership

We have been exploring collaborative opportunities building upon Arup's C40 UrbanLife Workshop where the toolkit could be used to explore opportunities for cities to improve the performance of their urban energy systems in an integrated way. The first workshop took place recently in Toronto (see http://www.arup.com/News/2009-09-September/25-09-09-Toronto_C40.aspx) and we shall use the data generated for a neighbourhood to explore the benefit of this approach. If this is successful, a series of workshops over the next year will provide ample opportunities for model testing.

Delft University of Technology

The cooperation with Delft University of Technology, started in April 2010 when Koen van Damjoined the Urban Energy Systems project as a visiting academic at Imperial College London, continued in 2011. Conceptual work on developing a *shared energy ontology*, aiming for interoperability between energy models and exchange of data sets on, for example, energy technologies, users, and demands, involed a comparison of an ontology developed for van Dam's PhD thesis (TU Delft) with the ontology developed for the Urban Energy Systems project at Imperial College.. A survey to create an inventory other existing conceptualisations of energy systems has been designed and implemented, mapping the needs for standardisation in the community. The survey, targeted at academics as well as model developers in industry, ran for a period of two weeks in February 2011 and received 50 responses. From the results of this survey, we can confirm our hypothesis that there is not yet one widely used conceptualisation for energy systems, but it showed ontologies have proven to be used successfully and the results suggest that a more widely used conceptualisation could benefit the larger community. The results of the survey were published at Formal Ontologies Meets Industry (FOMI2011)..

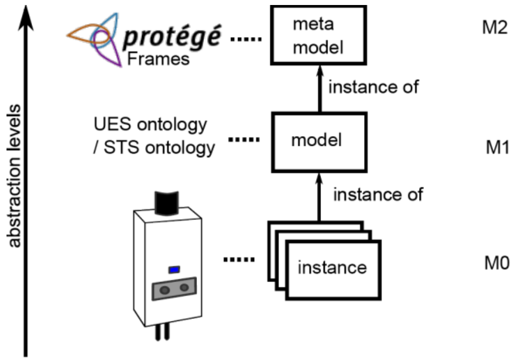


Figure 57. – Levels of abstraction of an energy technology (from van Dam and Keirstead, 2010)

Other dissemination activities include participation in the Sustainable Urban Systems section of the International Society for Industrial Ecology and in an NSF Research Coordination Network on sustainable cities.

8. Summary of outcomes and future plans

Key outcomes

SynCity

We have developed a holistic modelling framework for the design of urban energy systems. SynCity is a software tool for the design of urban energy systems. Using state-of-the-art optimization techniques, it allows users to identify system configurations that satisfy user demands and carbon constraints at minimum cost. The user interface allows users to choose from a range of urban energy technologies and capture the spatial and temporal characteristics of a real city.

Key features and benefits

SynCity offers several key features:

- *Assess multiple technologies simultaneously*. Urban energy plans are traditionally evaluated with discrete scenarios, each of which examines a reduced set of technologies such as a business-as-usual case with grid fuels, a renewable energy strategy, or a CHP strategy. With SynCity's integrated modelling framework, you can compare all available technologies in one analysis and identify the combination that best meets your needs.
- *Unique urban technology database*. One of the most time-consuming parts of any analysis is collecting the necessary technology data, such as capital and operating costs, capacities, and efficiencies. SynCity comes with an extensive built-in database of urban energy technologies including combined heat and power systems, cooling technologies, renewable energy technologies, and many more.
- Explicit modelling of the energy demand. In SynCity, the demand for energy arises from the explicit representation of underlying activities such as space heating and transport. This means that the model is sensitive to a wide range of policies that affect these activities.
- *Spatial and temporal granularity*. Many energy models neglect the spatial and temporal dimensions of energy demand, e.g. by considering the requirements of a city as a whole over an entire year. However SynCity uses an efficient representation of both time and space so that system performance and costs can be estimated more accurately, including vital technological features such as losses in distribution networks.
- *Cost minimization with carbon constraints*. For a given pattern of demands and available technologies, SynCity will calculate the lowest cost (capital and operating) system design. Users can additionally introduce carbon constraints so that policy targets can be easily assessed.

Rapid execution and scenario analysis. SynCity uses highly efficient optimisation techniques, which means that solutions are computed quickly thus facilitating "what if" style analysis of multiple alternative policy, regulatory and market scenarios.

Development of sustainable cities and energy systems programmes

The activities under this project have helped to underpin Imperial's expertise in the engineering of sustainable cities and the modelling, analysis and optimisation of energy systems. New initiatives that have emerged from these capabilities include:

- The Digital City Exchange project (http://www3.imperial.ac.uk/digital-economy-lab/partnernetworks/dce), an integrated five-year Digital Economy multi-disciplinary research programme within which researchers are exploring ways to digitally link utilities and services within a city, enabling new technical and business opportunities.
- Engagement with the TSB Future Cities Demonstration competition (http://www.innovateuk.org/content/competition/future-cities-demonstrator.ashx)
- The Celsius demonstration and innovation programme – an FP7 funded programme exploring the design and implementation of smart urban energy systems in five European cities.
- Participation in a new UK initiative in Whole Energy Systems Modelling

Forward plans

Development

Over the next few months, our focus will be on consolidating and finalising the work to date. For the SynCity tool kit, this means finalising the prototype graphic user interface on top of the existing code base and making any necessary refinements to its structure. Similarly we will publish journal articles on the existing models and case studies (as described above) and continue to explore exploitation routes for the technology. This will then be made available to selected users for testing and validation.

The main future development work will focus on replacing the existing agent-activity model with a more sophisticated version; this should greatly improve our ability to understand the effect of policy interventions on the behaviour of individuals. Some new exploratory work will also be done, examining the potential of a common energy systems modelling ontology (with a visiting researcher from Delft University of Technology) and exploring optimization and modelling strategies using real-time urban energy data (via a secondment at the University of Tokyo).

We will continue validating our results through case studies with external partners. This will not only help us to confirm that our models are functioning correctly, but it will also assist with the design of the graphic user interface and any commercialisation plans (see below). In other words, we want to use these collaborations to understand the work flow of practitioners and the needs of their clients.

Commercialisation/Exploitation

This is at an early stage of thinking. Nevertheless, there is clearly some unique IP associated with the property so we have started putting together a strategy for its exploitation. We see Syncity as a tool for *strategic planning* (not detailed design) of urban energy systems. Its position within the overall value chain is illustrated in Figure 58. We anticipate the first set of users would be urban planners (e.g. major architectural practices) and engineering consultants. They would use the tool to seek and undertake commissions for new developments and regional developments, where their clients are either major developers or metropolitan authorities.

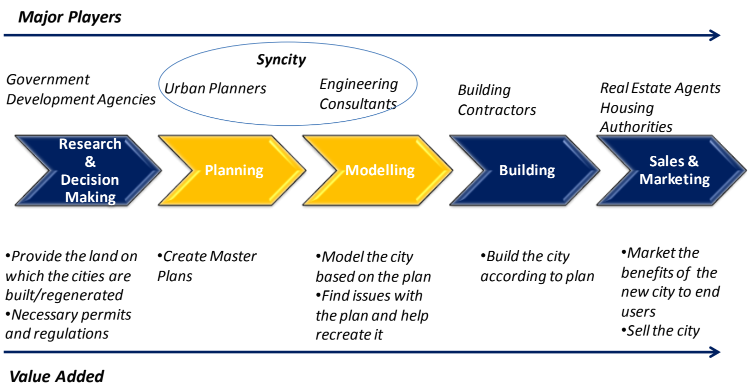
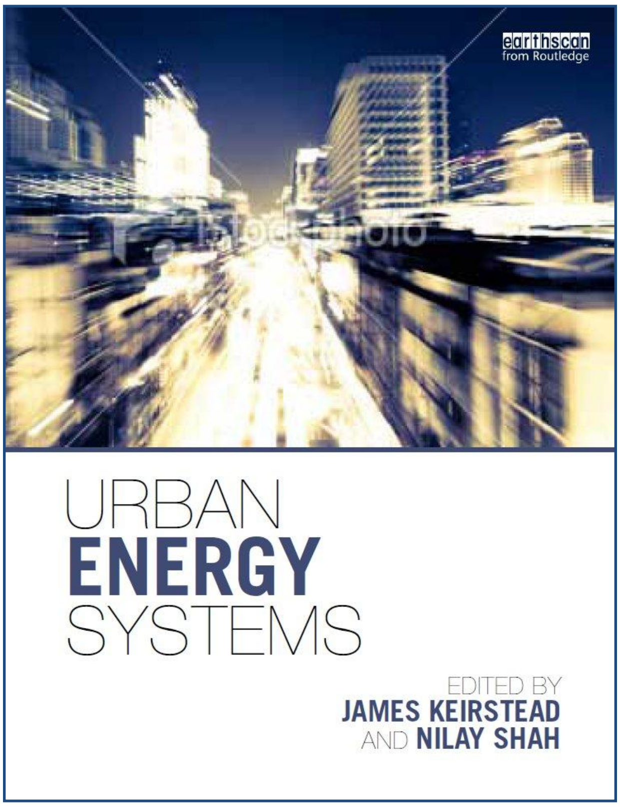


Figure 58. Syncity position in the planning value chain

Key publications

Our website (www.imperial.ac.uk/urbanenergysystems) lists the publications that have arisen to date from the Urban Energy Systems project, including a large number of journal articles, conference papers, book contributions, student theses, and other reports and online materials. These publications cover the project's full range of activities including the modelling work, assessment of urban sustainability indicators, contributions to UK policy debates, and business and consumer behaviour studies.

The project will conclude with the publication of a book, due out in February 2012. This covers the whole range of activities described in this report, and marks a major milestone in the challenges associated with energising future cities.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EDITED BY
JAMES KEIRSTEAD
AND NILAY SHAH