



bp-Imperial College Urban Energy Systems Project



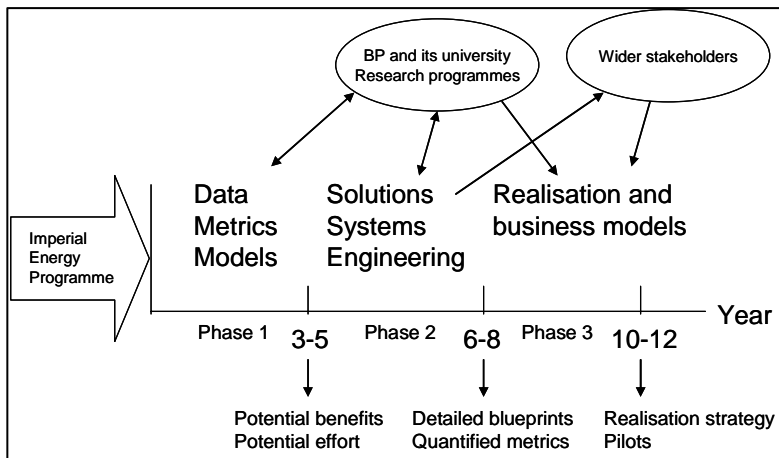
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## First Annual Report: Summary Version

March 2007

# 1 Executive Summary

The BP Urban Energy Systems project at Imperial will identify the benefits of a systematic, integrated approach to the design and operation of urban energy systems, with a view to at least halving the energy intensity of cities.



This challenging, multidisciplinary project is organised into three partially overlapping phases. The first phase (2006-2010) is concerned with identifying in broad terms the potential of the proposed modelling and optimisation approach, will deliver an estimate of the potential benefits to classes of cities, and will identify the means required to achieve these objectives. Later phases will address design and implementation.

The overall objectives of phase 1 are:

- To apply a quantitative, holistic analysis to identify what the achievable benefits (economic, energy efficiency, environmental impact, energy security, system resilience and robustness) of a fresh approach to urban energy systems are.
- To identify how these benefits might be achieved.
- To explore the power of modern optimisation techniques in urban context.
- To investigate the energy lessons to be drawn from the differences between cities such as London, Atlanta, and Beijing.
- To identify changes in energy market and supply structures and their implications for BP.

In order to achieve these objectives, we have organised our phase 1 plan into five major work activities:

- i. Understand the state of the art in urban energy systems analysis and modelling
- ii. Develop a conceptual framework to model urban energy systems
- iii. Develop a conceptual framework to capture the important interactions between urban infrastructures, citizens and institutions; in particular characterising the link between consumer behaviour and demand and developing appropriate theories of innovation and business models for large-scale, complex technological systems
- iv. Apply our methodologies to characterise real and representative cities
- v. Perform high level urban energy systems optimisation studies

The 12 months' work programme (essentially to spring 2007) focusses primarily on activities (i), (ii) and (iii) in the approximate proportions: 50:35:15.

Our review of the state of the art indicates that there are islands of excellence in the international global research arena. However, we have identified many shortfalls in "discipline-specific" research activities relevant to urban energy systems (e.g. techniques to design urban electricity distribution networks; models to understand consumer behaviour and demand, etc.). In addition, and more importantly, there are no significant holistic, multidisciplinary treatments of urban energy systems. We shall move forwards in this area by identifying the interactions between sector specific models and then integrating models towards this objective. Examples include:

- endogenising demand in complex conversion and supply models
- aligning infrastructure design and city evolution models
- modelling and optimisation across many indicators of performance
- ensuring that proposed developments are compatible with business and innovation theory

In more detail, some of the key findings from our review are:

- Current urban indicators are particularly limited by:
  - Weak or non-existent underlying model or theory of system dynamics and causality:
  - Delivered energy often being treated as a minor sub-theme of overall urban sustainability
- Systems ('Ecological') analyses of Urban Energy Systems should be extended
  - By understanding interlinkages with other biogeochemical cycles, particularly the water-, nitrogen-, and phosphorus cycle
  - By employing life-cycle analyses (LCA) to assess systematically a broader range of environmental risks
- The future power network could see building-integrated renewable and co-generation playing an important role in urban areas, and Distribution Service Organisations will need to address a more complicated control and interface problem.
- To date, many existing studies in energy network design are somewhat limited: analyses tend to be (a) based on simplified geometric demand distributions or network routing, or (b) applied only to a given network and not applied to establish general design rules.
- Historically transport, water, gas and electricity networks have been considered separately, resulting in missed optimisation opportunities.
- Demand side management (DSM) is vital to reducing energy intensity.
- Recent analyses of energy demand tend to be empirical case studies, with little generalization.
- Energy systems are undergoing a process of Schumpeterian 'creative destruction'; competitive advantages of incumbent technologies and business are eroded, while new opportunities for innovation are arising within the energy sector.

In activity (ii), we have started to develop frameworks for city modelling, in particular:

- Guidelines for proposed urban energy system indicators; we have developed a framework which will enable us to generate "fit-for-purpose" indicators which are energy-centric and which include a deeper understanding of dynamics and causality.
- Thermodynamic analyses to understand second law efficiencies; we have applied this technique to London and estimated an exergetic efficiency as low as ~30%.
- A new footprint concept based on closed loop processes; preliminary results indicate that with future technologies and holistic designs city energy footprints might be more considerably smaller than currently reported.
- Models for phased city-level spatial optimisation driven by energy considerations
- Specification of a synthetic city as an integrating test bed

In activity (iii) we have undertaken work on the analysis of consumer behaviour with respect to energy consumption, and analysed relevant theories of innovation and business models.

The forward plans for the next year include:

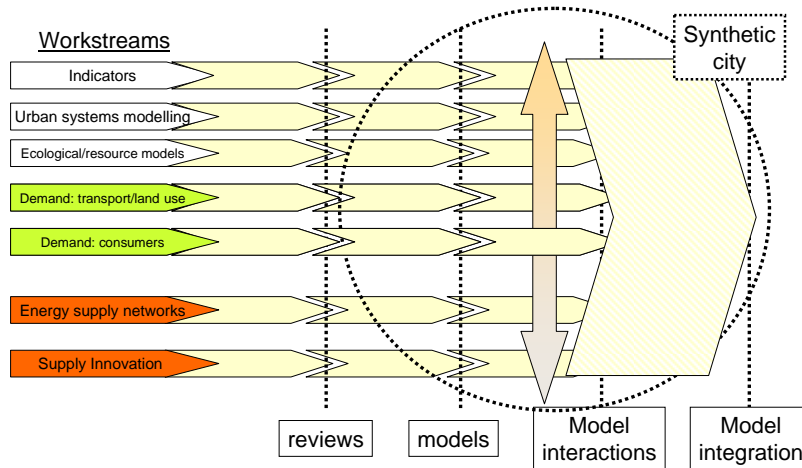
- Completion of the reviews of the relevant state of the art; publication of associated working papers
- Development of a set of integrated, model-based indicators for urban energy systems
- Progression of sector-specific models
- Concise theories of consumer behaviour leading to energy demand models
- Conceptual models of innovation in large, complex technological systems
- Formalisation of our synthetic city
- Exploration of sector-specific model interactions
- Progress towards an integrated urban energy system model
- Preparation for case study cities

## 2 Research highlights

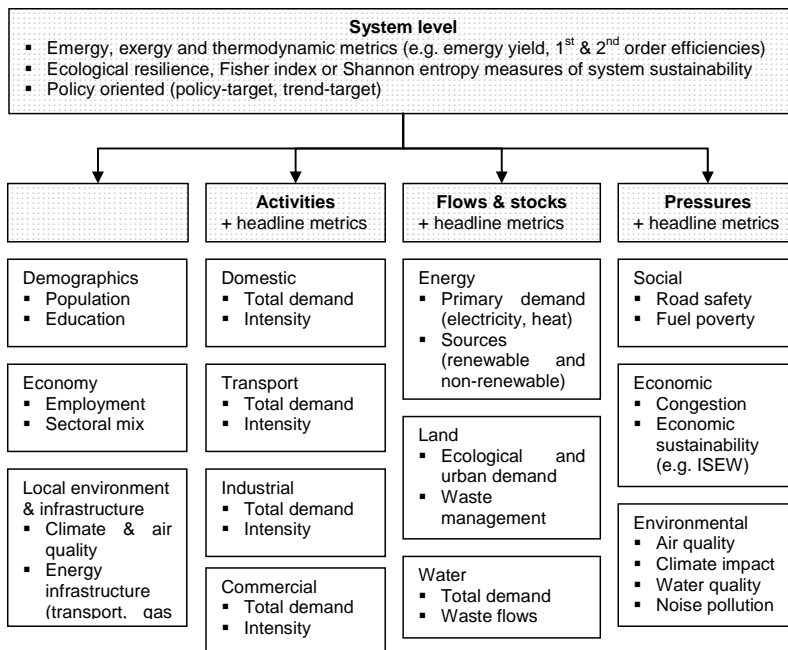
Our team has been recruited over the period April to December 2006, and is now broadly in place. In order to progress our activities effectively, the programme has been organised into a number of *workstreams*:

- Modelling oriented:
  - Analysis and development of indicators for urban energy systems
  - Analysis of city evolution and urban energy system modelling
  - Analysis and development of ecologically-inspired models for cities
- Demand oriented:
  - Understanding urban travel demand and land use-transportation interactions
  - Understanding and modelling urban energy demand from consumer perspectives
- Supply oriented:
  - Analysis and modelling of urban gas and power networks
  - Understanding and modelling innovation in complex technological systems

The project plan, in terms of these workstreams, is illustrated below.



In the next sub-sections, we present a few highlights of the first year. The full report, available upon request, reviews the work in much more detail.

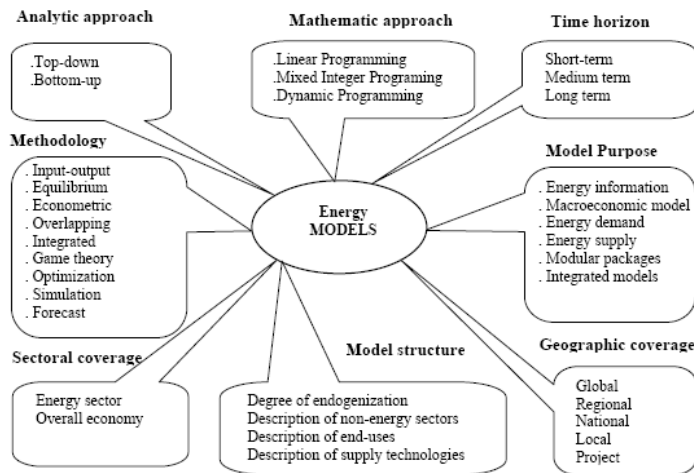


### 2.1 Urban Energy Indicators

The UES project seeks to describe the urban energy use and develop methodologies and recommendations for optimisation. The project takes a broad perspective, considering how innovation, social trends etc. might influence the demand for energy services. Consequently the project needs a series of metrics (or indicators) to describe these themes and the relationships between them. The figure alongside outlines the proposed indicator framework for the UES project, along with some example indicators.

## 2.2 Urban (Energy) Modelling and Optimisation

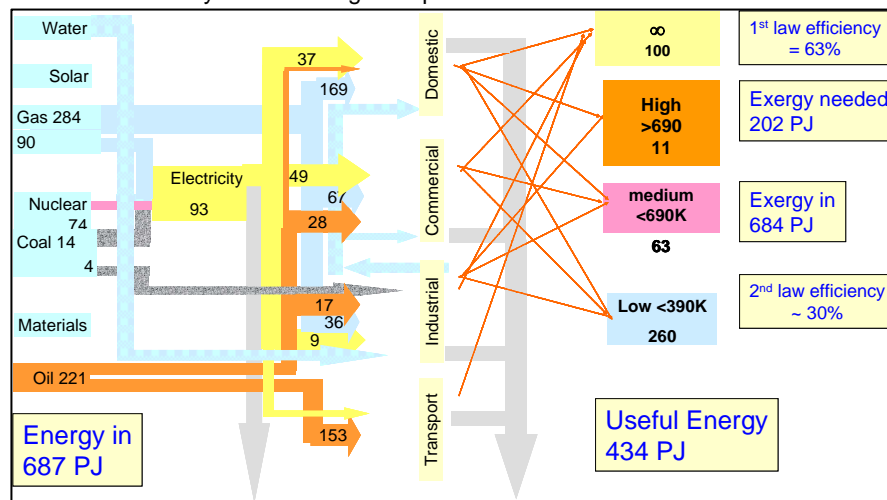
The importance of modelling and optimisation of urban energy systems can be seen as two-fold. Firstly it allows one to analyse and understand the current state of these systems. But also, and perhaps more importantly with regards to sustainability, it allows one to “predict, prescribe and invent” the urban energy systems of the future.



### City thermodynamics – exergetic analysis

The analysis of converting any process to an equivalent amount of work has been extended to processes within the city itself. This requires the required delivery temperature of each of the energy uses to be identified, along with the temperature of each discharge or waste stream. In effect rather than divide delivered energy amongst consumption classes (domestic, commercial etc) it is divided amongst uses (space heating, cooling etc) along with an

associated delivery and discharge temperature. Once this has been done it is straightforward to conceptualise a



reconfigured system using heat recovery (including from power generation and ambient sources) that can serve as an efficiency benchmark the minimum work that would be required to service these demands. A first calculation based on the London Energy Study suggests large cities are running at about ~30% of this baseline (see alongside). This figure is

possibly an overestimate since the work to provide transport does not yet include the possibility of journey optimisation. Nor does the figure reflect the thermodynamic value of waste streams. The advantage of this technique, borrowed from chemical engineering, is that it highlights the value of high temperature sources within a system. It does not have to assume changes in final energy use.

### Spatial infrastructure optimisation model

One of the goals of the UES project is to try to understand how cities evolve over time and to determine what forms are most energetically efficient. This type of problem is usually best addressed using optimisation, so some of the early modelling work in this project has been to develop a city model that can be optimised. Of course, cities are rarely in an optimal state and neither do they grow or evolve to reach another desired optimal state, but it may be possible to include such behaviour in the future. Nevertheless, the model that will be described next is useful for determining optimal structures and progress between them in an optimal manner.

#### Sample Results

A hypothetical city is modelled by assuming there are 1.5 million people living in a city divided in to 25 regions (defined by a regular 5-by-5 grid). Various assumptions are made about the data required, such as people's preferences for housing, what the wealth distribution is etc.

The problem is then to solve the model to obtain the current optimal city structure and to see how that evolves over a number of periods to a new optimum based a new set of parameters. Here, the energy cost of transportation was increased to 5 times the original value. The results are shown below.

Population density					Percentage green space				
0	0	0	0	0	100	100	100	100	100
0	110170	169492	169492	0	100	43	12	12	100
0	157480	103935	99514	0	100	19	25	37	100
0	121780	157480	0	0	100	30	19	100	100
161424	111870	137363	0	0	15	27	25	100	100

Number of residential buildings					Work provision				
0	0	0	0	0	0	0	0	0	0
0	3052	4695	4695	0	0	0	0	0	0
0	7591	10388	15091	0	0	0	967562	0	0
0	12217	7591	0	0	0	0	0	0	0
5888	11181	10147	0	0	0	532438	0	0	0

**Initial optimised state of city**

The four figures above show the “current” optimal state of the city. On the left are the number of people living in each region and total number of buildings in each. The city is “di-centric” with employment mainly in the centre and south-west. The two figures on the right show the amount of green space and the location of the employment service. The surrounding regions of the city can be seen to be all green space. The figures below show how the city evolves in time, from top to bottom, to obtain the new optimum structure under the higher transportation cost. The city becomes slightly more compact and employment both centralised and fragmented, with more “live-and-work” areas in the north-east and south-west.

Number of residential buildings					Work provision					
0	0	0	260	0	0	0	0	1610	0	T=1
0	2905	4695	4695	0	0	0	0	0	0	
0	7591	10387	14338	383	0	0	968073	0	2370	
108	14191	7591	0	0	0	100000	0	0	0	
5013	11372	9006	0	0	0	427947	0	0	0	
304	0	0	260	0	1884	0	0	1610	0	T=2
0	2905	4695	6914	0	0	0	0	20098	0	
0	7591	10434	12693	383	0	0	942527	0	2370	
10	13921	7591	0	0	0	100000	0	0	0	
5013	11365	8455	0	0	0	431512	0	0	0	
0	0	0	1816	0	0	0	0	0	0	T=3
0	952	4695	10779	1702	0	0	0	200000	0	
0	7256	10785	11934	0	0	0	750000	0	0	
10	13921	7157	0	0	0	100000	0	0	0	
5013	11068	5445	0	0	0	450000	0	0	0	

**City evolution - high transport energy cost scenario**

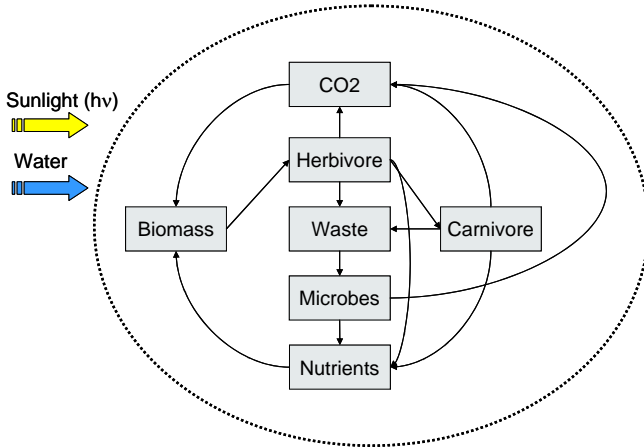
**Alternative ecological indicators: the closed loop process work-based footprint**

We have undertaken thorough reviews of ecologically-motivated models and accounting techniques for cities. Amongst the most notable is the ecological footprint, which relates resource and sink requirements in terms of area. Most studies of this nature indicate that the current “carrying capacity” of the planet has been more or less reached or even exceeded, and we are living on a finite bequeathed legacy of fossil fuels as well as generating an unsteady atmospheric state. These are interesting insights, and the ecological footprint method allows many interesting comparisons to be drawn between cities (albeit with care to iron out inconsistencies).

However, we believe this framework offers two areas of improvement:

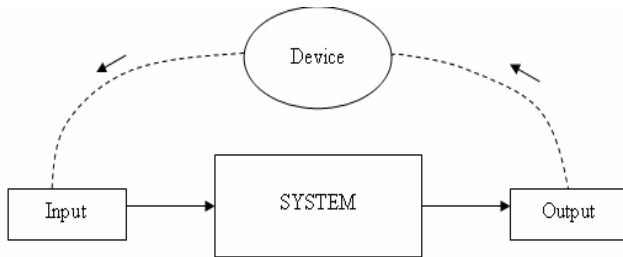
- i. The link with natural, “sustainable” environments that ostensibly formed the inspiration of the approach has been lost somewhat in the minutiae of accounting, coefficients, boundaries, conversion factors etc.
- ii. The methodology is somewhat backward looking in terms of technological possibilities, and therefore innately conservative and arguably pessimistic.

We are in the process of designing and applying a new concept which is more directly inspired by natural “closed loop” systems. Consider the simplified representation of a natural system alongside.



Although the system appears to be a closed loop with cycling of materials and energy, it clearly contains many irreversibilities and sources of entropy generation, and is not really in static equilibrium in the strict thermodynamic sense. Such systems are also normally subject to dynamic variations. However, a compensating non-equilibrium process of incoming solar radiative energy (which also supports the water cycle) takes place to sustain the system over very long periods of time.

In the case of the natural system, the “footprint” and the physical area are necessarily the same; the system evolves within this hard constraint.



We now apply this concept to a non-natural system such as a city. We can conceptualise this as a closed loop system, whereby a notional set of devices enable the continual conversion of the system outputs into “virgin” inputs. Our methodology must then identify system inputs and outputs and then determine the *work* required to restore the outputs into inputs. This can then be converted into an area footprint

corresponding to any convention that the user of this methodology chooses. Therefore the common unit of resource consumption is work, which is then converted into area. This approach is more forward-looking and helps identify steps towards “closed-loop” cities.



### 3 Future research programme

Our programme is characterised by the use of models (conceptual, qualitative and quantitative) to analyse, simulate and optimise important facets of urban energy systems. Our future work programme can be summarised by three key objectives:

- i. The development of fit for purpose models of aspects of urban energy systems (e.g. transport demand models, infrastructure optimisation models etc.)
- ii. The exploration of the interactions and interfaces of the models and techniques to integrate models – this strategy is more likely to succeed than attempting to build a single monolithic urban energy system model
- iii. The use of a synthetic city as an integrating test bed (our “experimental facility”)

#### 3.1 Workstream models

A critical part of our programme is deep, novel and quantitative research within each workstream. These activities will all result in outputs that can be considered models. The plans for these specific modelling activities are summarised below.

##### Indicators and ecological analyses

We shall develop a comprehensive set of indicators that address some of the major shortcomings identified. In particular we shall ensure that they are energy-centric and exhibit dynamic and explanatory characteristics. Our **targets for the next 6 months** are:

- Submit a paper reviewing indicators of relevance to our project
- Identify the first indicator set for project

In the ecological modelling area, we shall:

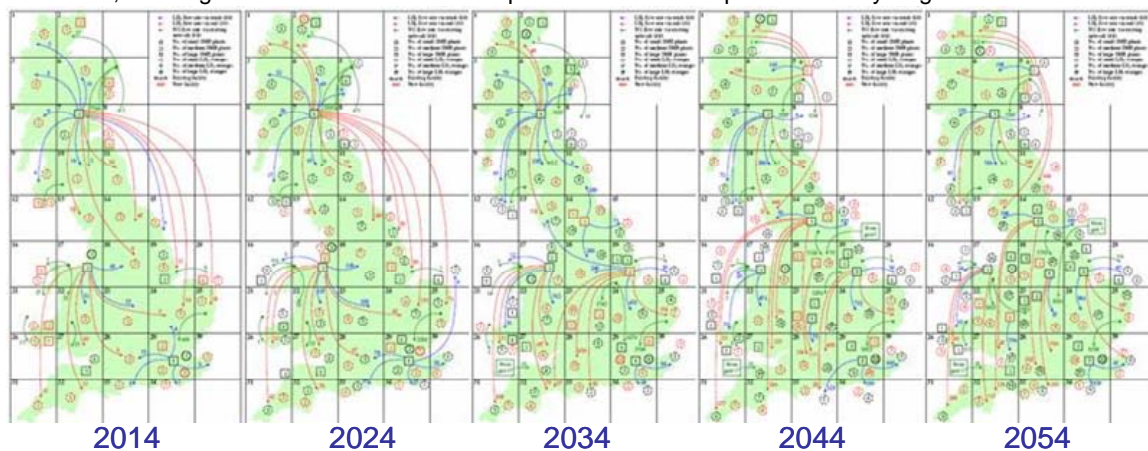
- Develop and refine the “closed-loop”, work-based metric
- Extend typical urban ecological models with biogeochemical cycles and LCA/eco-indicators

Our **targets for the next 6 months** are:

- Perform an LCA/eco-indicator study of a city (most likely Singapore, possibly with a comparison with London)
- Produce a revised version of our work-based metric with some key coefficients defined

##### City evolution and Infrastructure models

Here, shall extend our work on general infrastructure design models to the case of the city. This enables us to optimise the evolutionary development of the infrastructure, starting from an arbitrary initial condition. By way of illustration, the diagram below shows results of previous work for a possible UK hydrogen infrastructure.



Optimised evolving infrastructure: UK hydrogen example

Our **target for the next 6 months** is the demonstration of optimised infrastructure evolution on example city.



## Transport demand, infrastructure and land-use interaction models

At this stage we see three key directions for future work in this area:

- Exploit micro-simulation based activity-travel models – they predict the time spent by individuals on various activities both in-home and out-of-home
  - Allows estimation of the energy consumption not only of the transport activity but also of other activities, and overall urban energy implications of individual choices
- Development of improved models of agent-level behaviour (based on the random utility formalism and extensions)
  - accommodate broader energy-related aspects of urban consumption behaviour (e.g. vehicle and appliance choice) - not well-treated in existing modelling tools.
- Development of improved techniques for synthetic populations
  - Draw on existing literature but extend the scope to make energy-centric

Our **targets for the next 6 months** are:

- Completed reviews of transport demand and land use-transport modelling
- First version of improved agent-level behaviour models
- Specification for synthetic populations
- Outline understanding of overall energy implications in micro-simulation models

## Consumer behaviour and energy demand models

We shall progress our framework via three cases studies of energy services innovation. They will involve:

- Questionnaire survey on consumer characteristics, their perception of innovation and adoption behaviour – quantitative analysis
- Focus group interview to analyse cultural and contextual aspects of consumer contexts – qualitative analysis
- Secondary sources on the selected energy services to identify specific contextual information – qualitative analysis
- Semi-structured interviews with service provider – qualitative analysis

Targets for case studies include: “green energy” tariffs, car sharing and ESCO-consumer interactions. We shall work together with BP in this area; our **target for the next 6 months** is: preliminary results on first case study.

## Power and gas network design models

We shall develop models that can indicate performance (energy efficiency, cost effectiveness, flexibility, quality of service etc.) of different energy networks when subject to different patterns of use. As a first stage we will be able to use synthetic patterns of use of the type we expect to be available from the models developed by the other workstreams in the project. This will provide a means to examine why different cities might evolve different networks and to explore how optimisation might be approached, as well as how new technologies such as micro-CHP may be embedded and their impact on both gas and power networks. It will also provide some insight into how tighter integration of network models with other models (especially demand models, demand side management and infrastructure design models) might be achieved. Our **targets for the next 6 months** are:

- Completed reviews in urban energy networks and market systems
- Identifying the inputs required from other workstreams within the project
- First steps in model building
- Clear programme of work for two PhD students; identifying the most promising areas of study

## Models of innovation in large-scale technological systems and project ventures

We shall use “large technological systems” (LTS) and “complex product systems” (CoPS) approaches to study the UES and its technological and organisational components

- Adopt a qualitative method using interview-based case studies to explore firm strategies and emergent behaviour in the UES.
- Overall aim: improve our understanding of how incumbent/established energy providers are:

- Using project ventures to explore the frontier of energy systems technologies and markets.
- Evaluating and selecting project ventures from a range of new technologies (e.g. renewables).
- Developing new business models to grow initial project ventures into scaleable and profitable businesses.
- Changing the position in the value stream, developing new capabilities and organisational structure to create profitable and growing businesses based on the new technologies.
- This research could be used to develop a framework showing how a firm can manage the journey from an initial project venture to fully-developed business model. We would like to take advantage of our collaboration with BP to undertake an in-depth study along these lines. National Grid, as a complementary, established energy supplier is targeted for another study.

Our **targets for the next 6 months** are:

- Complete first 'exploratory phase' finding out what firms are doing in terms of new 'project ventures' - short interim report
- Start the research with BP and/or National Grid as soon as possible
  - Undertake initial interviews during April-June.

## 5.2 Model interactions and integration; synthetic city

Our work has been organised into workstreams combined with integrative activities. The workstreams are deep and discipline-specific because they aim to identify and advance the state-of-the-art in particular disciplines relevant to urban energy systems. However, it is by taking a holistic approach across workstreams that the maximum benefits will be achieved. We aim to do this in two phases:

- Build links between discipline perspectives, identify the interactions between models (essentially data transfers) and solve interacting models through iterative or simultaneous solution techniques
- Build on (i) to establish an integrating executive that effectively integrates the models.

### The synthetic city – an experimental test-bed

We now have a clear research structure with all workstreams populated moving ahead. But cities are integrated systems; their interconnections cause complexity and inefficiency which is why we need integrating activities.

One of our important integrating activities will be for the workstreams to come together and define and develop a synthetic model city. This serves two important purposes:

- It provides a contextual framework within which to explore integration issues
- It allows us to proceed with a variety of experiments without being dependent on large amounts of spatially- and temporally-dependent data.

The model city will be generated through a combination of sampling techniques and multi-agent modelling, and through careful selection of major distributions, joint distributions and marginal distributions, can be made to appear like a city of choice in terms of its aggregate parameters, but will have a data richness that would be almost impossible to obtain for a real city.

Our **target over the next 6 months** is to formulate a specification for the synthetic city, and to perform computational tests on sub-components (e.g. collections of households).