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Environmental Impact Assessment And Optimization Of Urban Energy Systems

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ABSTRACT

Over the last century, the world has witnessed rapidly increasing urbanization trends. Consequently, the urban governments of this époque require the measure and monitoring of their cities' expansion, as well as the impacts that this development has on the environment, the economy and the society. The energy sector in particular, plays a determining role in maintaining acceptable conditions in all these domains. The concept of sustainable development appears to combine a number of disciplines, which assess it in different manners. This research attempts to show how a combination of methods can provide further insight to a city's energy system. More specifically, the concepts of life cycle assessment and mixed-integer optimization are brought together and applied to a hypothetical urban energy systems case study looking at three different environmental impacts: global warming potential, resource depletion and air quality. The model chooses the types of energy technologies that are most suitable when aiming to minimize each environmental impact, showing that a carefully selected energy systems design can perhaps achieve lower overall environmental impact within an urban area. Life cycle assessment, material flow analysis and ecological footprint methodologies are further performed on two case studies: a UK eco-town and the city of Toronto. Five energy technology scenarios are compared based on these environmental impact assessment methodologies and conclusions drawn as to which scenario achieves the lowest values. Attention is drawn to stakeholder involvement and how interpretation of environmental impact is "vulnerable" depending to which priorities are set.

KEYWORDS

Urban energy systems; environmental impact assessment; optimization;

I declare that the work found in this thesis is my own and that all else is appropriately referenced.

ACKNOWLEDGEMENTS

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Secondly, I would like to thank my parents for their priceless and irreplaceable encouragement during the last few (but not only) years. Mom, without your motivating words and the faith in me that you expressed on a daily basis, none of this would have been realised to the optimum extent. All I can say is that you have set the bar very high with your own achievements, and I am trying to catch up - this work only brings me another step closer. ☺

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1. INTRODUCTION

1.1 Urban evolution

Over the last 100 years, the world population has experienced quickly increasing urbanization trends. These trends are only expected to maintain an upward trajectory in the coming decades. The drivers of this expansion vary and can be functions of the demographic, economic, social and political evolution of the world's metropolises. The fact remains that the global fraction of urban population rose from only 13% in 1900, to 49% in 2005 (UNDESA, 2006). Moreover, according to recent United Nations population projections, 60% of the world's population is expected to live in cities by 2030, amounting to 4.9 billion urban dwellers, as shown by Figure 1 below.

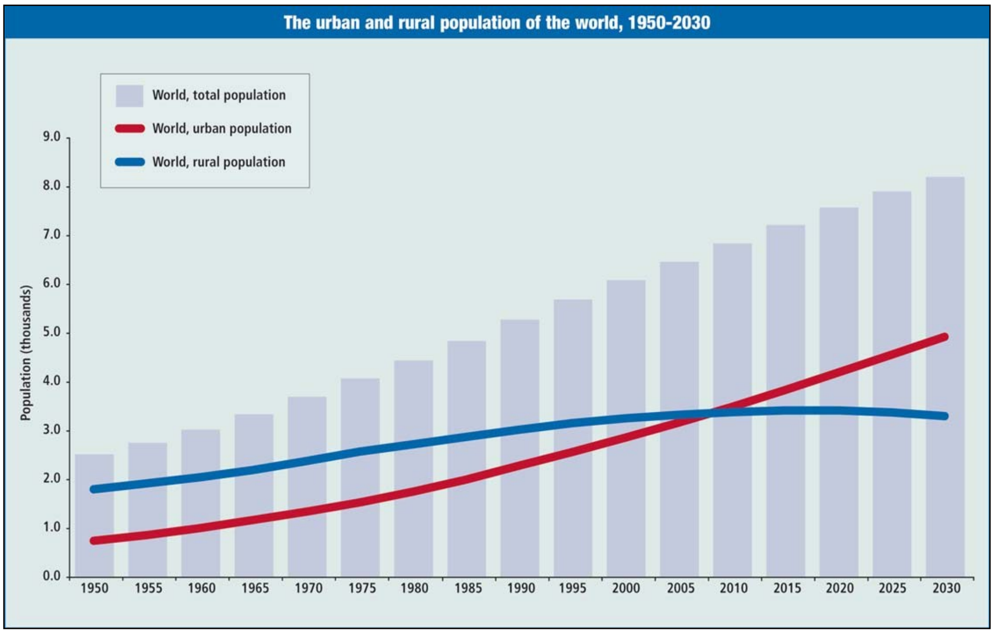

Figure 1 Changes in the world's urban and rural population, projected to 2030 (UNDESA, 2006)

Parallel to this urban blossom, the definition of sustainable development started to emerge and has encouraged urban governments to quantify a city's performance in those terms. The "Brundtland Report" (UNWCED, 1987) defined sustainable development as "meeting the needs of the present without compromising the ability of future generations to meet their own needs". In order to satisfy this definition, urban governments are looking for ways to measure the state of their city and evaluate its improvement against any desired targets. Targets such as reducing the environmental impact of an urban area are extremely common.

Naturally, the energy sector plays a pivotal role in the attempts to achieve sustainable development. Fossil fuels are seen as a "capital" resource that depletes over time, whereas renewables may be viewed as energy "income" to the planet (Hammond 2007). It has been estimated that 75% of global energy consumption occurs in cities and 80% of greenhouse gas emissions is due to cities in some way (UN Habitat, 2007). Approximately half of this amount results from the burning of fossil fuels in cities for urban transport and the other half arises from energy use in buildings and appliances - both these practices being necessary for maintaining the human quality of life in urban systems. Indeed, climate change, sustainable development and urbanization go hand-in-hand. Global energy demand forecasts shown in Figure 2 estimate an increase of primary energy demand of 60% in the next three decades as developing countries industrialise and rich countries continue to consume power (IEA, 2004).

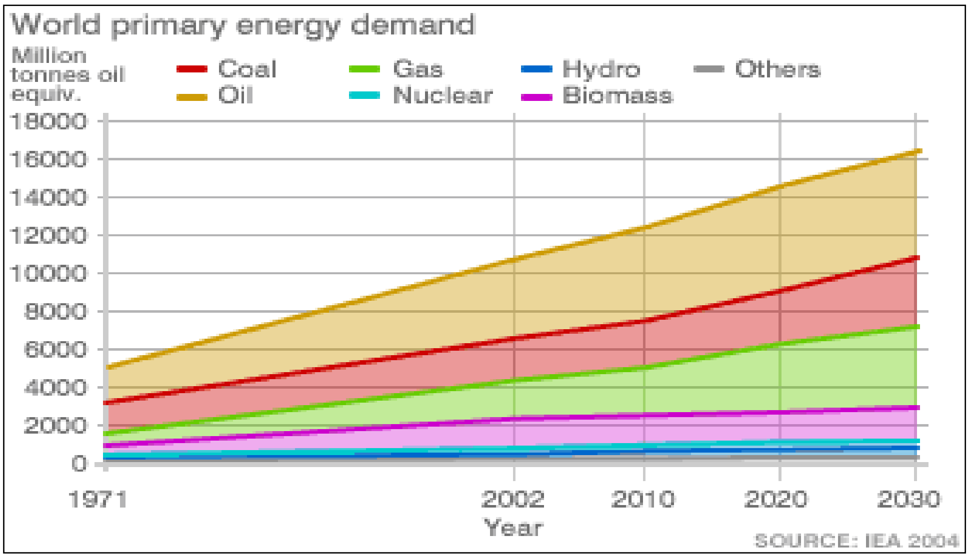

Figure 2: The forecast on how the world primary energy demand is expected to change by 2030 (IEA, 2004).

In the 2011 World energy outlook, the IEA expects the most important changes to be in the patterns of energy generation and production. The use of all fuel types develops, yet fossil fuels are expected to still be responsible for more than one-half of the overall primary energy demand increase, even under the New Policies Scenario. Traditional and modern renewable energy increases its share from 13 per cent in 2008 to 18 per cent in 2035, and nuclear energy appears to grow from 6 per cent to 7 per cent of total primary energy demand.

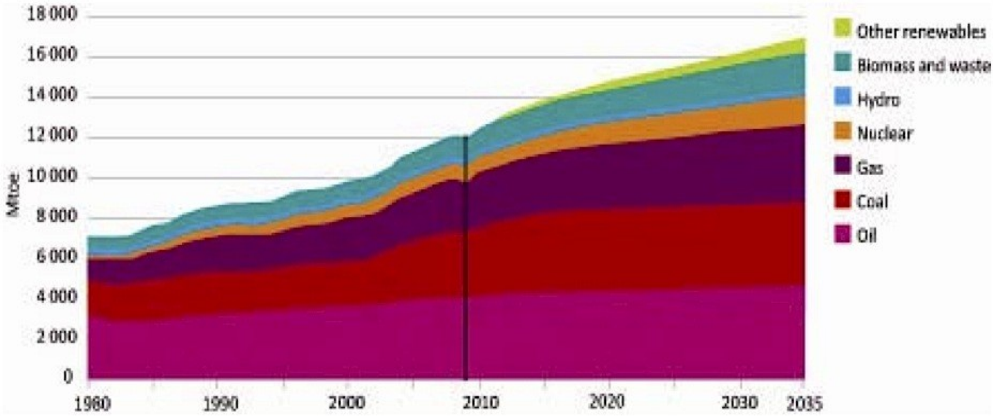

Figure 3: World primary energy demand by fuel in the New Policies Scenario, 1980 to 2035 (IEA, 2011).

If indeed the global panels take significant action to stabilise greenhouse gas concentrations at 450 ppm, these trends will further be enhanced. Under the 450 ppm Scenario, global coal use falls from approximately 27 per cent of the global mix to around 16 per cent by 2035. Generally in this scenario, world use of fossil fuels falls rapidly, while low-emission sources of renewable and nuclear energy blossom.

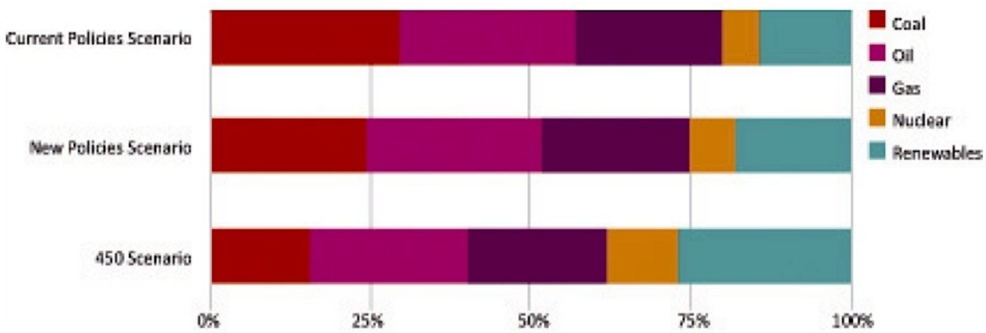

Figure 4: Shares of energy sources in world primary energy demand by scenario, 2035 (IEA, 2011).

Given that urbanization and energy demand go hand-in-hand, and rising numbers are expected in both, a better understanding of urban energy systems is at the forefront of urban government agendas.

1.2 Cities as eco-systems: the history and concept of urban metabolism

Cities can be thought of as having a metabolism, like plants or animals. Studies on the concept of urban metabolism have been conducted since 1965, investigating water trends, materials, energy and nutrient flows within cities. Typically cities have exhibited increasing per capita metabolism with respect to water, wastewater, energy and materials over time. Through these studies, metabolic processes that potentially put the sustainability of cities in danger can be pinpointed. These include changing ground water levels, depletion of local materials, regular and irregular accumulation of toxic materials and nutrients, and effects such as the summer urban heat island. By understanding urban metabolism, urban policy makers are to better comprehend the extent to which local resources are approaching exhaustion and hence, devise relevant strategies to delay exploitation. The fact is that urban metabolism studies have not been produced for enough cities worldwide and ideally, more are required.

1.3 Background to this Work

The research topic under investigation is part of the BP Urban Energy Systems (UES) project, which is taking place at Imperial College London in collaboration with BP. The UES project is trying "to document and understand in detail how energy, people and materials flow through a city [and] to show how the efficiency of both existing and new-built cities can be radically improved" (BP, 2006).

Energy systems have been defined as the "combined processes of acquiring and using energy in a given society or economy" (Jaccard, 2005). This short description can be interpreted in a variety of ways within an urban setting, such as the analysis if physical flows in a small neighbourhood (Thomas, 2003) or when taking the approach of social scientists and policy makers, it can become the study of how these flows are affected by "town-planning, environmental goal-setting, employment policies, and so on" (Alexandre *et al*., 1996). For the BP UES project, these and additional views are considered in order to "identify the benefits of a *systematic, integrated* approach to the design and operation of urban energy systems" (Shah *et al*., 2006).

The energy systems modelling approaches used in the UES project are suitable for estimating future urban demands for energy services and possible infrastructures. These approaches provide opportunities to consider more efficient use of energy as well as alternative technologies.

This project aims to investigate the energy balances observed in urban systems in terms of resources entering a city and wastes leaving, and estimating the environmental impact of activities associated with these inputs/outputs. These will form part of the wider study into sustainable and highly efficient future urban developments.

Surprisingly, not enough is known on how cities consume energy, impact the environment and whether the way energy is used is optimal. Together with other components, a huge part of this project is dedicated to the development of the Synthetic City toolkit, which models urban energy systems.

1.3.1 The Synthetic City Toolkit

The Synthetic City (SynCity) platform (Keirstead *et al*., 2009) was developed by a group of researchers within the BP UES project at Imperial College, as a toolkit for the modelling and optimization of energy systems within the urban environment. It comprises three major components, a layout model, an agent activity simulation model and the resource technology model.

Figure 5: Framework of Synthetic City modelling toolkit (UES Annual Report, 2010).

A brief description of the major components follows:

The layout model

As its title suggests, the layout model is used to optimize the spatial design of the city based on cost, energy reduction and environmental or other parameters. The input is in the form of GIS geographical data on the existing city infrastructure and it is utilized to optimize the location of additional facilities of interest (such as residential, commercial and other buildings).

The agent activity model

This stochastic sub-model provides an estimate of the daily demand-generating activities of individuals within a city, such as the annual average passenger-kilometres for travel, as well as resource demands over time and within each zone of a city. This gives rise to spatial and temporal energy demand patterns, forming the output of the model.

The Resource-Technology Network (RTN) Model

This final sub-model of SynCity is used to explore different scenarios for the optimal provision of energy to cater for the demand patterns generated by the agent activity model.

Conceptually the model splits up the city into smaller cells, of any size or shape and they do not need to cover the full area within certain city borders. Each of these cells stands for a dynamic entity within the models, with its own resource demands, resource conversion and storage technologies. Additionally, there can be connections between individual cells for the transportation of resources, plus external connections for bringing in or sending out resources. Resources can represent any material or energy resource that is consumed or generated, including wastes (e.g. CO_2, waste water, waste heat, refuse, etc.). Resource demands that arise in each cell must be satisfied, by converting other resources, transporting those resources from other cells, importing them from outside the city, or taken up from a storage, if there is availability of that resource.

The model developed in this work can constitute a part of the RTN model in the SynCity framework, since the type of results obtained can complement performance measures (e.g. GHG emissions) that form a part of it.

1.4 Aims and Objectives

This project targets to investigate the energy balances observed in urban systems in terms of resources entering a city and wastes leaving, and estimating the environmental impact of activities associated with these inputs/outputs. These will form part of the wider study into sustainable and highly efficient future urban developments.

The broad aim of this research is to provide a set of methodologies and tools for the planning and operation of urban energy systems using the Life Cycle Assessment (LCA) concept, modelling and optimization techniques. It is based on detailed analyses and studies of urban environments, the various processes within them and some application of appropriate modelling and optimization formulations to reveal the trends and behaviour of urban energy systems.

This report starts with a concise literature review, covering relevant pieces of work performed by other researchers in the field and follows with a description of the methods used to facilitate this project. The work covered describes the emissions inventory and the applications of the LCA methodology in a simple, hypothetical urban energy systems case study. Subsequently, it is shown how modelling frameworks inspired by natural ecology can help us valuate the sustainability of urban energy systems as applied to a UK eco-town. After first discussing the similarities between cities and ecological systems, a review of relevant environmental impact assessment methods is presented before demonstrating how these methods can be combined with optimization techniques to assess the life-cycle impacts of an urban energy system. Finally, the discussion ties together the results and considers what they reveal in the broader context of urban energy systems.

The rationale for choosing a UK eco-town as a case study lies in the fact that much of the data was readily available since this eco-town has been a popular object of research at Imperial College.

There is a large amount of energy-related data available from international organizations such as the IEA, the World Bank, the OECD, as well as, from academics that have looked into material and energy flow analysis (e.g. Schulz, 2005). Currently, work is being done at Imperial College on providing an enhanced idea of the way that urban energy systems operate at Energy Futures Lab, also under the BP UES project and so this research will form a useful complement.

Taking the above into consideration, the research question for this investigation has been set as:

"Which EIA methodology (or combination of methodologies) is most relevant and appropriate to the design of a particular UES and how easily can it be applied"?

This thesis has been structured as follows:

Chapter 2 contains a concise literature review relevant to this field of work;

Chapter 3 describes the approach and methodology to this study;

Chapter 4 presents and analyses the results;

Chapter 5 discusses the findings of this research;

Chapter 6 provides the concluding remarks and recommendations for future work;

Chapter 7 gives the list of references used throughout this work.

2. LITERATURE REVIEW

2.1 Precedents of Similar Work

2.1.1 Systems Optimization Coupled with LCA

Various authors have attempted to incorporate LCA within a formal process systems optimization framework, with the Methodology for Environmental Impact Minimization (MEIM) being one of the earliest attempts, performed by Stefanis et al. (1995). The authors highlight the need to account for the waste associated with INPUTS to a process (upstream wastes associated with raw materials, energy generation, etc.) and not solely the OUTPUTS. The MEIM is illustrated using a case study of VCM production. As such, the methodology involves three steps: (i) definition of the system boundary (expanded to include raw material extraction and energy generation), (ii) environmental impact assessment, where for each pollutant released from the process, a vector denoting its corresponding environmental impact (air and water pollution, solid wastes, global warming, photochemical oxidation and stratospheric ozone depletion) can be obtained leading to an aggregated impact vector, and (iii) synthesis of a more environmentally benign process, where the incorporation of the environmental impact criteria in process optimization takes place in order to find the best plant design that achieves both minimum global environmental impact and minimum economic cost.

A significant result that arose from Stefanis' work is the fact that when only local emissions are minimized, the minimum global impact is not necessarily achieved. Through his VCM case study, it is shown that the Zero Avoidable Pollution (ZAP) approach is not always the best environmental choice. (refer to Figure 6)

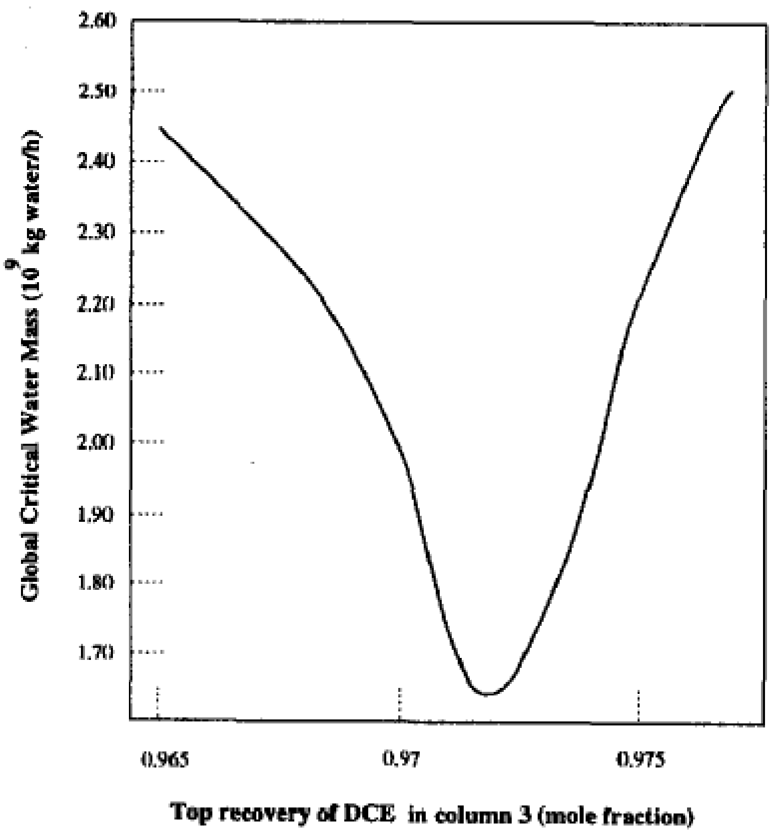

Figure 6: The objective of minimizing only output emissions of the conventional VCM process is in fact sub-optimal (Stefanis, 1995).

According to Stefanis, "a minimum site-specific discharge limit exists beyond which the global environmental impact increases due to trade-offs in waste generation over the whole life cycle".

Azapagic & Clift (1995) brought LCA and Linear Programming (LP) together in order to environmentally optimize a product system. The problem lies in how the allocation of environmental burdens such as resource depletion, emissions, solid waste, etc., in a system with more than one product should take place. By representing the whole productive system through a LP model and solving through its marginal[1] and shadow values, the environmental performance of the product system can be analyzed and managed. The authors first identify the environmental burdens and then aggregate them into different impacts such as greenhouse effect, ozone depletion, etc. Weights are then assigned to the impacts according to their importance (based on environmental and socio-economic objectives that are of interest to the decision-makers) and the shadow values are used to identify products and activities in the system which make the greatest contribution to the overall environmental impact. LP accounts for the different states of the system and multi-objective LP helps to resolve conflicting demands on system performance.

The same authors further refined their work (Azapagic & Clift, 1999) to incorporate the issue of how to allocate burdens between different inputs to the system/systems which produce more than one functional output, as well as to reflect both the use and production of recycled materials. Still by using marginal allocation of environmental burdens based on physical causality, the authors propose either the avoidance of allocation through system boundary expansion or

[1] Infinitesimal, small variations about existing operations that are always linear.

solution based on the real behaviour of a product system, i.e. its causal relationships. System expansion can be illustrated by an example taken by Azapagic & Clift (1999). If System I produces products A and B and System II produces only product C, and A is to be compared with C, then allocation can be avoided by broadening the system so that an alternative way of producing B is added to System II. (refer to Figure 7)

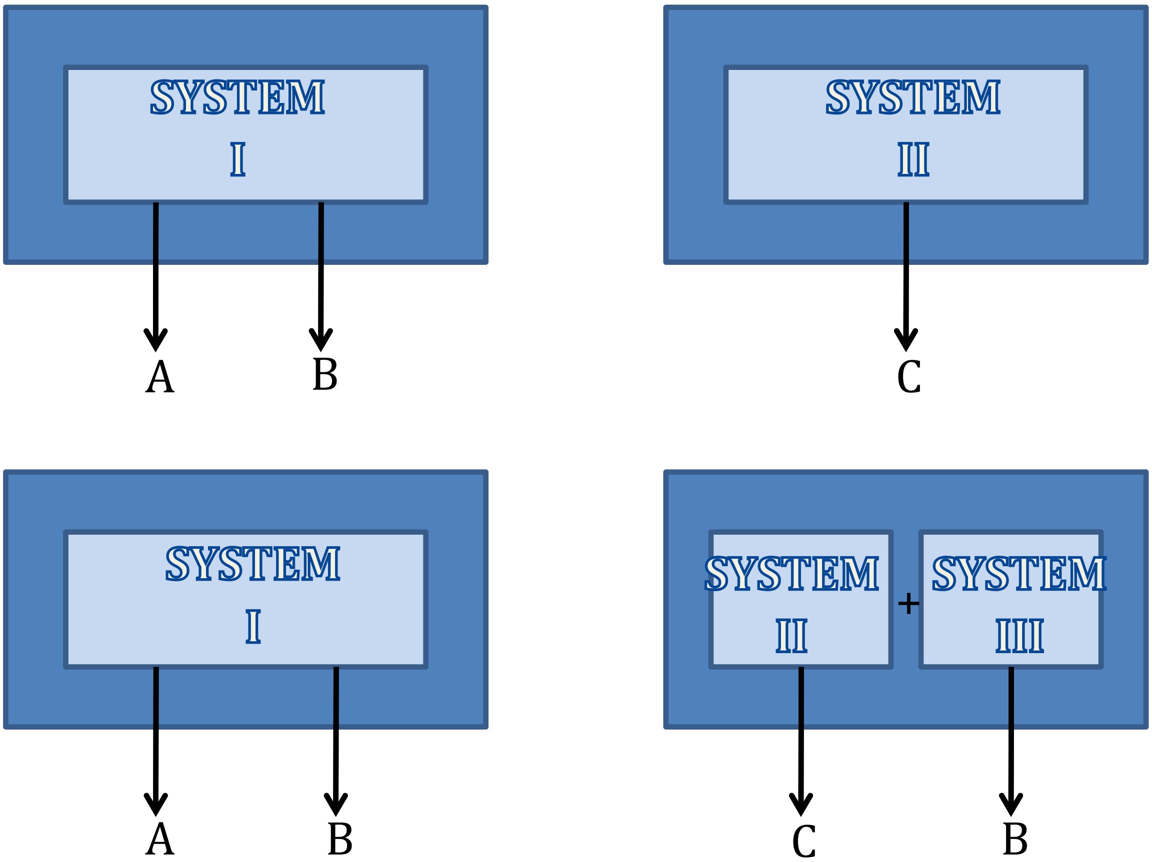

Figure 7: Avoiding allocation by enlargement - expanding the boundaries (Azapagic & Clift, 1999).

The comparison now takes place between System I producing A + B and Systems II and III producing C + B.

The methodology includes linearization of the process model to relate the total burdens in the system to the material and process properties through marginal allocation coefficients and minimizing environmental burdens at the Inventory level of the LCA and environmental impacts at the Impact Assessment level. Optimization is proposed at the Improvement Assessment level. By using three examples of systems (multiple input, multiple output and multiple use) marginal analysis reveals whether the environmental burdens are process or material related and possible places for system improvement. Marginally allocated burdens also depend on how the system is operated and not just on the internal structure of the system. The authors criticize their work by stating that detailed data on sub-processes must be available to establish the type of causality and that marginal allocation cannot always be used to describe average or discrete changes (which may be non-linear) in a system.

Through their work in 1999, Azapagic and Clift introduce the concept of coupling LCA and Multi-objective Optimization (MO), thus establishing the link between environmental impacts, operation and economics of the system. A general MO problem of a system can be stated with the following relationships (Azapagic & Clift, 1999):

$$\textit{Minimize} \qquad \boldsymbol{f}(\boldsymbol{x},\boldsymbol{y}) = [f_1, f_2, ... f_p] \qquad (2.1)$$

s.t.

$$\boldsymbol{h}\ (\boldsymbol{x}, \boldsymbol{y}) = 0$$
$$\boldsymbol{g}\ (\boldsymbol{x}, \boldsymbol{y}) \leq 0 \qquad (2.2)$$
$$\boldsymbol{x} \in \boldsymbol{X} \subseteq \boldsymbol{R}^n$$
$$\boldsymbol{y} \in \boldsymbol{Y} \subseteq \boldsymbol{Z}^q$$

where $\boldsymbol{f}$ is a vector of economic and environmental objective functions; $\boldsymbol{h}\ (\boldsymbol{x}, \boldsymbol{y}) = 0$ and $\boldsymbol{g}\ (\boldsymbol{x}, \boldsymbol{y}) \leq 0$ are equality and inequality constraints, and $\boldsymbol{x}$ and $\boldsymbol{y}$ are the vectors of continuous and discrete variables, respectively. The equality constraints may be defined by energy and material balances; the inequality constraints may describe material availabilities, heat requirements, capacities, etc. A vector of $\boldsymbol{n}$ continuous variables may include material and energy flows, pressures, compositions, sizes of units etc., while a vector of $\boldsymbol{q}$ integer variables may be represented by alternative materials or processing routes in the system.

The system is first optimized on each objective to identify the feasible regions, while other functions are ignored. One of the functions is then arbitrarily chosen as an objective function and all other objectives converted to constraints. A number of optimizations, in which the RHS of the objectives-constraints are varied within the feasible region, are performed to yield a range of non-inferior solutions. With this methodology, objectives do not have to be aggregated into a single objective and the Best Practicable Environmental Option (BPEO) and Best Available Technique Not Entailing Excessive Cost (BATNEEC) can be identified. The advantage of this technique is that multi-objective optimization in environmental system management in the LCA context offers a set of alternative options for system improvements, rather than a single optimum.

The case study used to illustrate LCA and MO is a system that produces five boron products. MO was performed on three objectives: total production (P), costs (C) and Global Warming Potential (GWP). Results are shown in Figure 9 below:

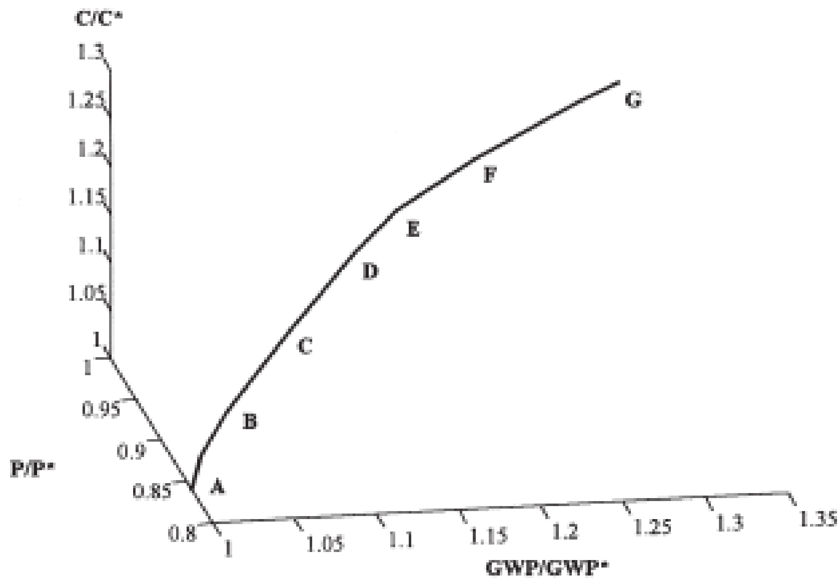

Figure 8: Non-inferior curve for ulti-objective optimization (Azapagic & Clift, 1999).

Points A and G represent optimum values of GWP and P respectively. At point A, GWP is at a minimum, but so is production. By moving away from A, along the non-inferior curve, both GWP and total production increase and at G, production is at a maximum and GWP also increases. Additionally, the costs also increase from A to G by an average of 20%. Clearly, all points on the non-inferior curve are optimal in a Pareto sense and decision makers can select any solution from A to G, depending on how much of one objective they are prepared to give up in order to gain another. If all objectives are considered of equal importance, then one of the possible ways to choose the best compromise solution is to identify the operating conditions at which all objectives differ from their optima by the same percentage. In that case, it would be the solution at point C. However, if some objectives are considered more important than the others, any other solution on the non-inferior curve can be chosen as the best compromise.

When referring to a Pareto optimum, it is implied that no individual can be made better off without making at least one other individual worse off. In this case, the Pareto or non-inferior surface is optimal in the sense that none of the objective functions can be improved without worsening the value of some other objective function.

As a follow-up to her previous work, Azapagic (1999) presented LCA and its application to process selection, design and optimization as a powerful decision-making tool for more sustainable performance of process industries. The methodology is given as follows:

- Carry out a LCA study
- Formulate MO problem in LCA context
- MO on environmental & economic criteria
- Multi-criteria decision analysis and choice of best compromise solution

The way to reach the choice of best compromise solution is to optimize the system on a number of objective functions so that optimum solutions are found on the Pareto surface. The choice of environmental objectives to be optimised depends on the Goal and Scope of the study. Thus, optimisation can be performed either at the Inventory or Impact Assessment levels, in which case the environmental objectives can either be burdens or impacts. Therefore, local and global system improvements are found by first moving the system conditions on the Pareto surface, and then moving along it. Since all objectives on the surface are Pareto-optimal, certain trade-offs between the objectives are needed to identify the best compromise solution.

The above methodology is illustrated using the examples of BPEO for SO_2, NO_x and VOC abatement, where it is concluded that the choice of BPEO depends on the boundaries, the operating state of the system and on the background economic system in which it operates. In addition, it is shown that from an environmental point of view, minimization of output emissions only as normally carried out in conventional system optimization, can lead to suboptimal solutions. The author further identifies the limitation that the LCA approach assumes that the environmental burdens and impacts functions are linear, i.e., they are directly proportional to the output of functional unit(s) and that there are no synergistic or antagonistic effects.

Hugo et al. (2004) present a process design methodology for identifying opportunities where step-change improvements in both process economics and environmental impact can be achieved by using multi-objective optimisation techniques. The approach extents the previously developed MEIM for process selection. Accepting that a conflict between economic and environmental concerns inherently exists, the task is to modify a process through the use of alternative materials. Extensions to the MEIM methodology include the explicit formulation of new environmental performance criteria, and a multi-objective optimization algorithm based upon a domination set strategy for detecting Pareto optimality. Their work uses liquid-liquid extraction operations as an example to show how the full plant-wide integration of alternative materials satisfies both environmental and economic performance.

One year later, Hugo et al. (2005) investigate the viability of a hydrogen economy by applying multi-objective optimization techniques to the strategic planning of a hydrogen infrastructure. Their model is based on the fact that hydrogen can be manufactured by a variety of primary energy feedstocks and distributed in a variety of forms using different technologies. The question they are aiming to answer is what are the most energy efficient, least damaging yet most cost effective pathways to deliver hydrogen to the consumers?

Again, a conflict of objectives arises since the most profitable infrastructure is not necessarily the least environmentally damaging. Therefore a set of trade-off or

Pareto solutions, and not just a single solution, exist, lacking a one, "best" alternative.

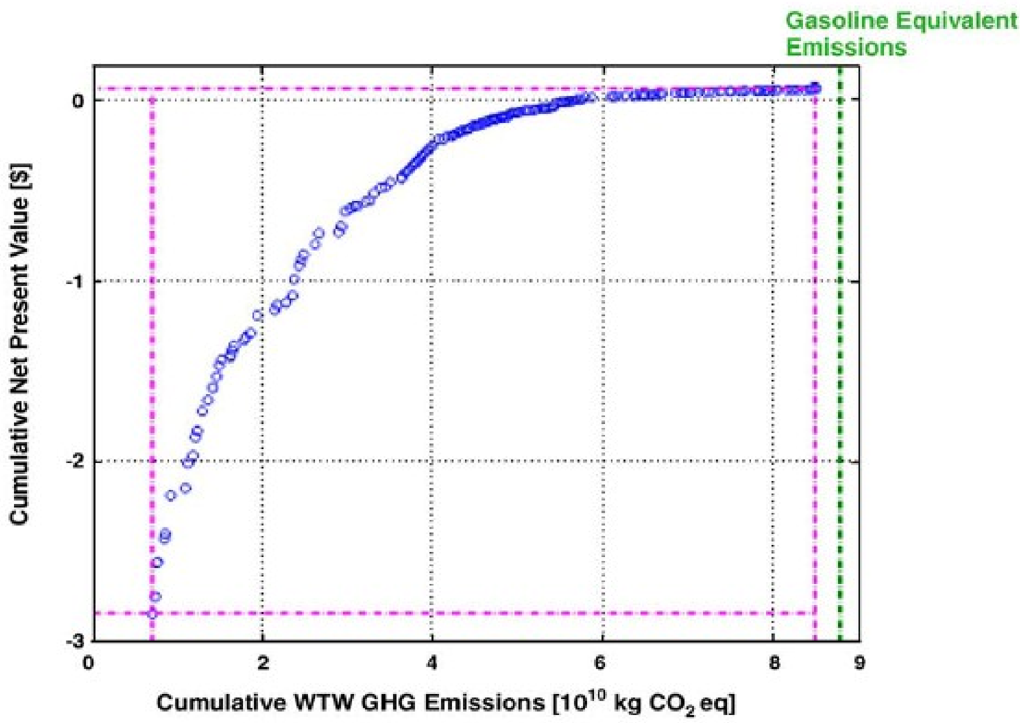

Figure 9: Optimal trade-off results for the case study (Hugo et al., 2005).

The case study depicted in Figure 9, is based on a geographical region with six production sites identified for potential installation of central production technologies. Thereafter, the demand for hydrogen was forecasted for each city. It can be seen that at one extreme of the curve, the maximum Net Present Value (NPV) solution and the corresponding infrastructure choice can be found. At the other extreme, the minimum GHG emissions solution with its corresponding infrastructure choice can be found. Moving along the trade-off curve, from one extreme to the other involves a series of alternative infrastructure design and investment strategies, all of which are perfectly feasible.

Azapagic et al. in their more recent work (2007) attempt to identify options for reducing the total environmental footprint of human activities in urban areas, rather than shifting environmental impacts from area to area or from one life cycle stage to another. A hypothetical city with 500,000 inhabitants is used as an example to map the flows of pollutants in the urban environment. The authors integrate LCA, Substance Flow Analysis (SFA), Fate and Transport Modelling (F&TM) and Geographical Information Systems (GIS) to achieve the aforementioned. The methodology is described below:

- Spatial definition of sources in GIS
- Definition of sources using a combined LCA-SFA methodology
- Quantification of burdens/impacts at source using the LCA-SFA methodology
- F&TM and quantification of the environmental impacts at the receptor end for mapping in GIS

The authors highlight the importance of ensuring that the reduction of pollution in the urban environment is not carried out at the expense of “other” environments. One of the advantages of this methodology is that, while it focuses on the urban environment, it also helps to understand wider environmental implications.

In the most recent developments of energy systems optimization, Liu et al. (2009) have presented a paper on multi-objective optimization of polygeneration energy systems. This new technology involves the co-production of electricity, synthetic liquid fuels, but also hydrogen, heat and chemicals in one process, while promising low emissions. In this work, economic and environmental factors are optimised simultaneously, showing a variety of likely technology combinations and types of equipment. The model is formulated as a non-convex mixed-integer nonlinear programming problem and the optimal Pareto trade-off curves are produced using global optimization tools and parallel computation techniques.

Research by Keirstead et al., (2009) on evaluating integrated urban biomass strategies for a UK eco-town showed that by increasing the integration of energy services, e.g. through the use of combined heat and power systems, improves the efficiency of urban energy systems. The particular eco-town is supplied with heat and power from biomass sources in this case. Results show that even though biomass offers a promising low-carbon solution, significant uncertainties remain in cost, carbon performance and resource availability.

Keirstead et al. (2010) further wrote a paper on the implications of CHP planning restrictions on the efficiency of urban energy systems. They highlight the need for urban planners to understand trade-offs between limitations on CHP plant-size and the performance of the energy system. They use a mixed-integer linear programming model to evaluate a number of energy systems designs under a range of scenarios. They conclude that cost penalties of up to 10 per cent may be implied by restrictions on maximum CHP plant size, as well as energy-efficiency penalties of up to 60 per cent.

Weber and Shah (2011) published a journal on optimisation based design of a district energy system for an eco-town in the United Kingdom. The trade-offs between the optimal layout of a city in terms of transport and the resulting district energy system are analysed. A layout model is consequently used to define the best layout of the city that achieves reduced transport requirements. Additionally, the optimal mix of technologies that satisfy the energy sector is calculated using process optimization techniques. It is concluded that increasing the density of the cities to reduce transport energy requirements affects the opportunities created by particular renewable energy technologies for heat and power services.

More recently, Liang et al. (2012) used the case of Shanghai Lingang New City and performed simulations to demonstrate a promising low-carbon emission solution which is the combination of gas engine heat pump and building cooling, heating and power. Keirstead et al. (2012a) produced a paper evaluating biomass energy strategies for a UK eco-town with an MILP optimization model. The paper examines an integrated resource modelling framework that identifies an optimized low-cost energy supply system including the choice of conversion technologies, fuel sources, and distribution networks. Keirstead et al. (2012b) later on, produced a review of urban energy systems models, covering approaches, challenges and opportunities. The results indicate that there is significant potential for urban energy systems modelling to move beyond single disciplinary approaches towards a sophisticated integrated perspective that more fully captures the theoretical intricacy of urban energy systems. Additionally, Keirstead and Calderon (2012) published a journal on capturing the spatial effects, technology interactions and uncertainty in urban energy and carbon models, specifically on the city of Newcastle-upon-Tyne. Their results show that their alternative optimization-based approach can help policy makers draw more robust policy conclusions, sensitive to spatial variations in energy demand and capturing the interactions between developments in the national energy system and local policy options. The authors suggest that further work should focus on improving our understanding of local building stocks and energy demands so as to better assess the potential of new technologies and policies.

Taking the above different pieces of research into consideration, one can observe that there is a gap of optimizing *urban* energy systems, while taking into account a *holistic* view of environmental impact and this is what this research will aim to cover.

2.2 Early studies of urban metabolism

The first such study was performed forty-five years ago by Wolman (1965) triggered by rapid expansion trends in urban America of that time and concerns about the difficulties of providing adequate water supply to an average US megacity. His article analysed the metabolism of a hypothetical American city, quantifying the overall fluxes of energy, water, materials and wastes into and out of an urban region of one million people. According to Wolman, “the metabolic requirements of a city can be defined as the materials and commodities needed to sustain the city’s inhabitants at home, at work and at play… The metabolic cycle is not completed until the wastes and residues of daily life have been removed and disposed of with a minimum of nuisance and hazard” (p.179). Although he focused largely on water, as the input required in the greatest quantities, estimates for food and fossil energy inputs were also calculated, as well as those fluxes associated with chosen outputs such as refuse and air pollutants.

Subsequent to Wolman’s work, more studies were conducted around the world, and over several decades, a body of literature emerged aiming to capture the significance of urban metabolism. One of the earliest attempts was that of ecologists Duvigneaud and Denaeyer-De Smet (1977) who produced a study of Brussels, Belgium. In their work they took into consideration the detailed quantification of urban biomass, not ignoring even organic discharges from cats and dogs shown in Figure 10. Newcombe et al. (1978) studied the city of Hong Kong thus determining the flows in and out for construction materials and finished goods. This particular study was elaborated more recently by Warren-Rhodes and Koenig (2001), demonstrating that the per capita consumption of food, water and materials had risen respectively by 20, 40 and 149 per cent in the period between 1971 and 1997. Newman (1999) also portrayed growing trends in per capita resource inputs and waste outputs while observing the city of Sydney, Australia. More recently, Sahely et al. (2003) reported that while studying the city of Toronto, some per capita outputs (namely, residential solid waste) had decreased between 1987 and 1999, even if most inputs to this North American city were constant or increasing. Additional metabolism studies of cities include those for Tokyo (Hanya and Ambe, 1976), Miami (Zucchetto, 1975), nineteenth century Paris (Odum and Stanhill, 1977), Greater London (Girardet, 1995; Chartered Institute of Wastes Management, 2002), Vienna (Hendricks *et al*., 2000) and part of the Swiss Lowlands (Baccini, 1997).

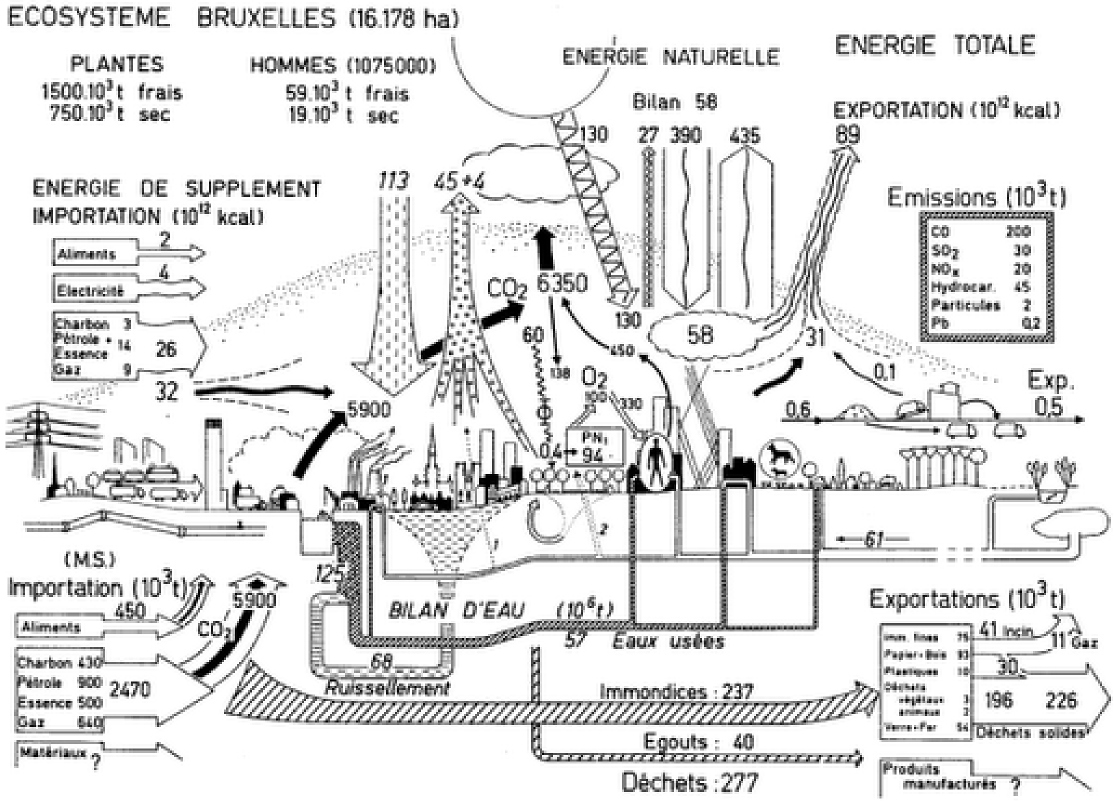

Figure 10: The urban metabolism of Brussels, Belgium in the early 1970s (Duvigneaud and Denaeyer-De Smet, 1977).

Together, all these studies provide a quantitative approach to describing the metabolism of a diverse set of global cities, and their respective changes over time. Generally, the metabolism of cities is analysed in terms of the four fundamental flows: those of water, materials, energy and nutrients. Variations in the flows can be expected from city to city because of age, the level of economic development, the availability of technologies, cultural factors, and, in the case of energy flows in particular, factors such as climate or urban population density also affect the metabolism (Kennedy *et al.*, 2007). More importantly, urban metabolism studies have demonstrated themselves as being a valuable tool to pinpoint the metabolic processes that potentially threaten the sustainability of cities

2.3 Introducing the Case Study: The UK Eco-Town

Similar to the concerns of most governments in the world, the UK government has identified factors that contribute to climate change and as part of national energy policy goals, has promoted “eco-towns”. These new urban areas are typically aiming to achieve an 80% reduction of CO_2 emissions (from 1990 levels) and an ecological footprint that is two-thirds of the national average.

The UK eco-town used as a case study in this research has an area of approximately 90 hectares; it is intended to house 6,500 people and is located in central England, near Bedfordshire.

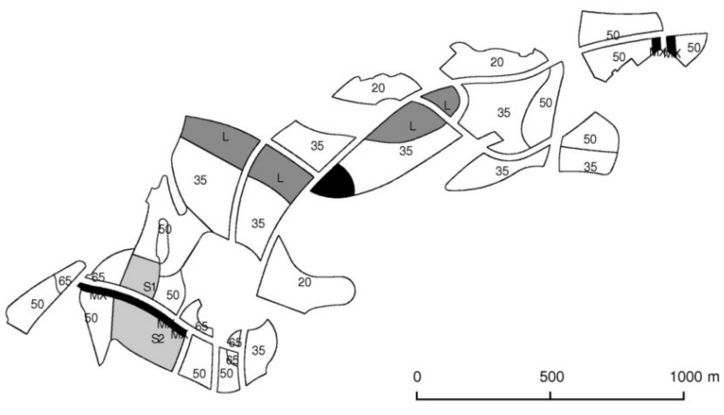

Figure 11: The UK eco-town.

2.4 City Footprints

There is strong agreement between natural and social scientists that sustainability is directly related to the maintenance of natural capital (Wackernagel *et al*., 1999). This includes species, ecosystems and other biophysical entities. Indicators such as the ecological footprint attempt to provide a simple framework for the accounting of natural capital and the formal definition of the ecological footprint is: "The total area of productive land and water required continuously to produce all the resources consumed and to assimilate all the wastes produced by the defined population, wherever on Earth that land is located" (Wackernagel and Rees, 1996: 228).

The concept of ecological footprints is based on material and energy flow accounting. If a city is thought of as having an "industrial metabolism", then it can be compared to a large animal grazing its pasture (Wackernagel and Rees, 1996). Even though the city uses up resources, all the energy and matter is returned to the environment. So, as Wackernagel and Rees (1996: 228) state, the question becomes: "How large a pasture is required to support the city indefinitely – to produce all its 'feed' and to assimilate all its wastes sustainably?" Figure 12 below demonstrates the concept:

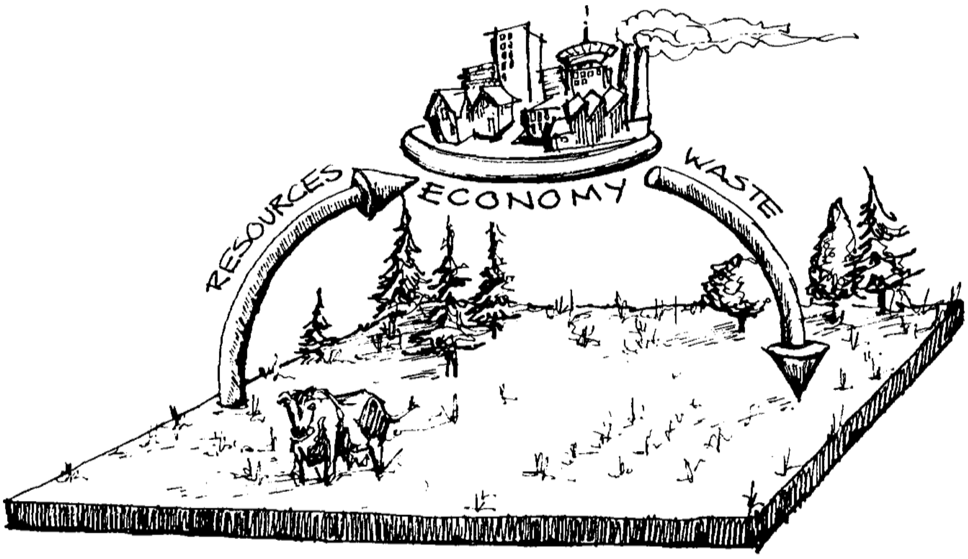

Figure 12: Comparing the city to a large animal to portray the concept of the ecological footprint (Wackernagel and Rees, 1996: 228).

In their work, Wackernagel and Rees, calculate ecological footprints based on the following equation:

$$EF(ha/capita) = \frac{ProductiveLand(ha)}{Country'sPopulation(millions)} \tag{2.3}$$

where productive land is a good proxy for natural capital and many of the resource flows and essential life support services that this capital provides (Wackernagel *et al.*, 1999). Productive land categories include cropland (for producing crops), grazing land (for animal products), forest (for producing wood and paper), fishing ground (for producing marine fish and seafood), CO_2 absorption land (for absorbing CO_2 emissions released by burning fossil fuels) and built-up land (Wackernagel *et al.*, 1999).

Concise definitions relevant to the topic of biocapacity and ecological footprinting are provided by the Global Footprint Network (2012) and can be found below, for consistency and reference:

- **Biological capacity or Biocapacity:** The capacity of ecosystems to produce useful biological materials and to absorb waste materials generated by humans, using current management schemes and extraction technologies. "Useful biological materials" are defined as those demanded by the human economy. Hence what is considered "useful" can change from year to year (e.g. use of corn (maize) stover for cellulosic ethanol production would result in corn stover becoming a useful material, and thus increase the biocapacity of maize cropland). The biocapacity of an area is calculated by multiplying the actual physical area by the yield factor and the appropriate equivalence factor. Biocapacity is usually expressed in global hectares.
- **Biological capacity available per person (or per capita):** There were ~ 12 billion hectares of biologically productive land and water on this planet in 2008. Dividing by the number of people alive in that year (6.7 billion) gives 1.79 global hectares per person. This assumes that no land is set aside for other species that consume the same biological material as humans.
- **Biologically productive land and water:** The land and water (both marine and inland waters) area that supports significant photosynthetic

activity and the accumulation of biomass used by humans. Non-productive areas as well as marginal areas with patchy vegetation are not included. Biomass that is not of use to humans is also not included. The total biologically productive area on land and water in 2008 was approximately 12 billion hectares.

- **Ecological Footprint:** A measure of how much area of biologically productive land and water an individual, population or activity requires to produce all the resources it consumes and to absorb the waste it generates, using prevailing technology and resource management practices. The Ecological Footprint is usually measured in global hectares. Because trade is global, an individual or country's Footprint includes land or sea from all over the world. Ecological Footprint is often referred to in short form as Footprint. "Ecological Footprint" and "Footprint" are proper nouns and thus should always be capitalized.
- **Global hectare (gha):** A productivity weighted area used to report both the biocapacity of the earth, and the demand on biocapacity (the Ecological Footprint). The global hectare is normalized to the area-weighted average productivity of biologically productive land and water in a given year. Because different land types have different productivity, a global hectare of, for example, cropland, would occupy a smaller physical area than the much less biologically productive pasture land, as more pasture would be needed to provide the same biocapacity as one hectare of

cropland. Because world bioproductivity varies slightly from year to year, the value of a gha may change slightly from year to year.

On a global scale, the 2006 Living Planet Report (WWF, 2006) highlighted that since the late 1980s the world has been in overshoot. According to the report, the Ecological Footprint has exceeded the Earth's biocapacity by approximately 25% from 2003 onwards. What this means is that the demand is growing in such a rate, that the Earth's regenerative capacity cannot keep up with it. In other words, people are turning resources into waste faster than nature can turn waste back into resources (WWF, 2006). Figure 13 below shows in absolute terms, the world's average per person Ecological Footprint and per person biocapacity over a 40-year period. It can be deduced from the graph that in 2003, the world's average EF per capita was at 2.2 global hectares per person, whereas it is estimated that only 1.7 hectares per person are available (Global Footprint Network, 2007).

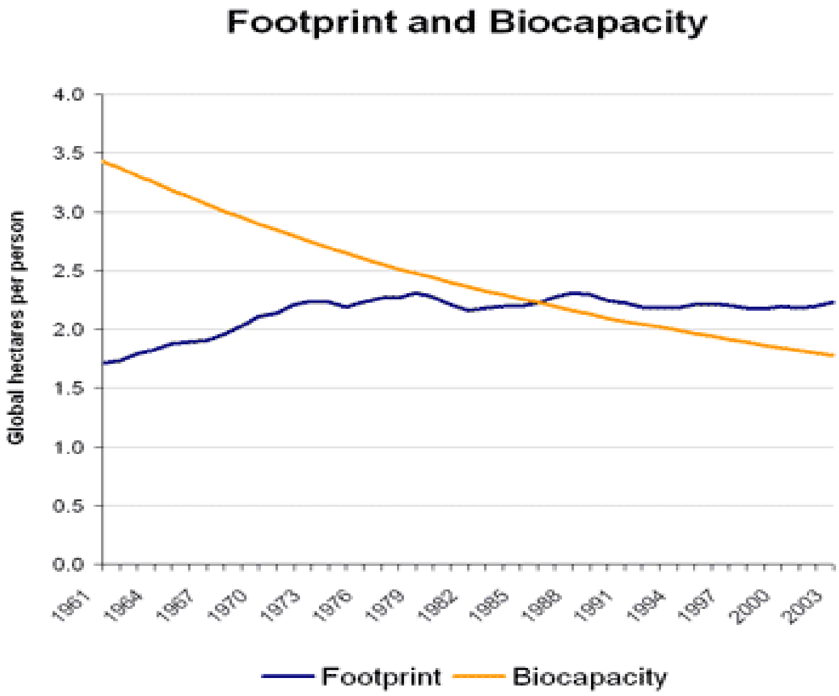

Figure 13: The global overshoot of the ecologican footprint over the Earth's biocapacity from 1988 onwards (Global Footprint Network, 2007).

Overshoot, occurs when a population's demand on an ecosystem exceeds the capacity of that ecosystem to regenerate the resources it consumes and to absorb its carbon dioxide emissions.

The Ecological Footprint is often used to calculate global ecological overshoot, which occurs when humanity's demand on the biosphere exceeds the available biological capacity of the planet. By definition, overshoot leads to a depletion of the planet's life supporting biological capital and/or to an accumulation of carbon dioxide emissions.

Overexploitation of resources, such as overfishing and overharvesting, pollution from pesticides, oil spills and toxic chemicals are typical reasons leasing to significant biocapacity reductions.

2.5 Optimization solution techniques

An introduction to the use of optimization models in energy systems analysis is given below. The use of a basic linear programming framework is vital to the application of optimization and LCA methods to urban energy systems.

2.5.1 Mixed-Integer Programming

The fundamentals of this type of technique can generally be used to translate complex (energy) systems into models (hypothetical or real) and thus generate various scenarios of interest.

Mixed-integer optimization problems typically take the form of:

$$\min_{\boldsymbol{x},\,\boldsymbol{y}} \quad f(\boldsymbol{x}, \boldsymbol{y}) \tag{3.1}$$

$$\begin{aligned} s.t. \quad & \boldsymbol{h}(\boldsymbol{x}, \boldsymbol{y}) = 0 \\ & \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}) \leq 0 \\ & \boldsymbol{x} \in \boldsymbol{X} \subseteq \boldsymbol{R}^n \\ & \boldsymbol{y} \in \{0, 1\}^q \end{aligned} \tag{3.2}$$

Where $\boldsymbol{x}$ is a vector of n continuous variables, $\boldsymbol{y}$ is a vector of the integer variables, $\boldsymbol{h}(\boldsymbol{x}, \boldsymbol{y}) = 0$ represents the equality constraints, $\boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}) \leq 0$ represents the inequality constraints, and $f(\boldsymbol{x}, \boldsymbol{y})$ is the objective function (Floudas 1995). The integer variables often denote binary variables, with a value of zero or one.

Mixed-integer programming (MIP) has been used in various aspects of process systems engineering, including heat exchanger network integration, flexibility analysis of chemical processes, design of batch processes, chemical synthesis and the planning of future energy systems.

The above formulation can be divided into two categories, mixed-integer linear programming (MILP) and mixed-integer nonlinear programming (MINLP). For the former, both the objective function and all constraints are linear. The latter involves nonlinear terms in the objective function or the constraints.

A MILP problem can be expressed more specifically as:

$$\min_{\boldsymbol{x}, \boldsymbol{y}} \quad \boldsymbol{c}^T \boldsymbol{x} + \boldsymbol{d}^T \boldsymbol{y} \tag{3.3}$$

$$\begin{aligned} s.t. \quad & A\boldsymbol{x} + B\boldsymbol{y} \leq \boldsymbol{b} \\ & \boldsymbol{x} \geq 0 \end{aligned} \tag{3.4}$$

$$\boldsymbol{y} \in \{0, 1\}^q$$

Where $\boldsymbol{x}$ is a vector of n positive continuous variables, $\boldsymbol{y}$ is a vector of q binary variables, $\boldsymbol{c}$ and $\boldsymbol{d}$ are vectors of $(n \times 1)$ and $(q \times 1)$ parameters. A and B are matrices of appropriate dimension and $\boldsymbol{b}$ is a vector of p parameters.

The two types of methods typically used to solve MILP problems are branch and bound methods and cutting plane methods. As the name suggests, in the branch and bound method, the problem is presented as a binary tree and lower bounds are generated upon solution of a relaxed problem at each level. The upper bounds are produced at the bottom level of the tree and a comparison of upper and lower bounds produces the final results. On the other hand, in a cutting plane algorithm, new constraints that are added to the problem at each step, achieve reduction of the feasible region until a binary optimal solution is found. Commercial solvers such as CPLEX contain both these algorithms which can tackle MILP scenarios in a robust and efficient way. Hence, integrated software like GAMS can easily provide solutions to this type of problems. Upon obtaining an optimal solution, it can be assumed to be a global minimum due to the convexity observed in MILP problems.

On the contrary, specific formulations dictate convexity in MINLP problems and two types of algorithms are utilised to provide a solution, the branch and bound (BB) and the outer approximation (OA). Similarly to the MILP problems, the BB works by solving its relaxed editions iteratively. The difference is that at each step a MILP master problem and a nonlinear programming (NLP) sub-problem is obtained, to give lower and upper bounds to the original problem. The OA algorithms use a different technique to give upper and lower bounds and lead to the optimal solution by the continuous renewal of these bounds.

There are two disadvantages that accompany MINLP algorithms as opposed to MILP ones. Primarily, a global solution cannot always be guaranteed if the MINLP is not convex, yet in real life non-convex problems are very common. Additionally, due to the excessive numbers of NLP sub-problems, extensive computation is required with solutions much more complex than those for linear programming (LP) problems. The desirable action is to transform the MINLP problem to a MILP one with as little as possible loss of information.

3. METHODOLOGY

3.1 Data Processing

This research project involved the gathering of data and its assessment, which initially attempted to provide a solution to the question:

"What are the NEW components that differentiate the design of urban energy systems from process and/or other types of systems?"

Data was needed to provide a quantitative and qualitative framework to the problem. Only official statistics were used, even though they may not have been entirely accurate.

A significant difficulty encountered during this project was the actual collection of raw data needed to formulate a model. Although major effort was put into finding information from a single reliable source, it was impossible to find the range of data describing social, environmental and economic aspects of an area from one database. The reasoning behind a single source was to avoid inconsistencies in methodologies and approaches. However, it was ensured that all statistics came from recognized international sources that applied similar, if not identical, methodologies in their analyses. Emphasis was put into maintaining the quality of the numbers, since a major component of the project relies on them.

The SimaPro 7.1 package with Ecoinvent 2.1 data was primarily used, to meet the objectives of the project and completion of the tasks did not depend on results from other people in related tasks. For simplicity, MS Office Excel was used to organize and process the collected data.

A preliminary "structure" for the model was created, in order to help in the identification of the types of data needed. This is shown in Figure 14 below.

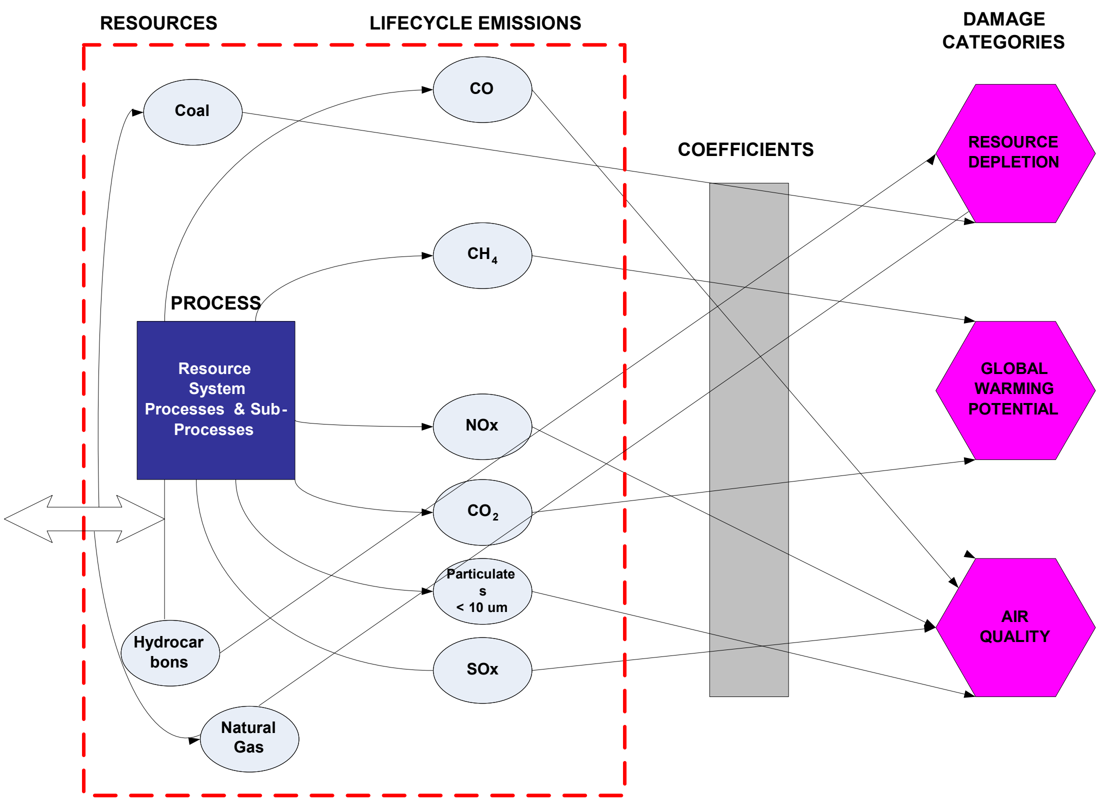

Figure 14: The structure for the model, depicting the connections between system, emissions and damage categories.

The interactions between the various emissions and damage categories are captured in this illustration.

3.2 Environmental Impact Assessment Methods

When attempting to understand the detailed impacts of an urban energy system, descriptive techniques such as urban metabolism are often not applicable. Even though the technique gives an excellent overview of the energy flows needed to sustain a city, it does not allow the researcher or policy-maker to understand the potential environmental impacts of alternative energy system combinations, such as, the difference between a district heating system based on biomass sources and one based on natural gas. The purpose of this section is to illustrate the way in which Environmental Impact Assessment (EIA) methodologies and Urban Energy Systems (UES) modelling and optimization techniques can fuse. In order to achieve that, one step back must be taken to evaluate these methodologies on UES.

Although a vast number of techniques exist to measure the environmental "friendliness" of a system, three specific EIAs were chosen for the purposes of this research:

- Material Flow Analysis (MFA)
- Ecological Footprints (EF)
- Life Cycle Assessment (LCA)

These methodologies can be applied to urban energy systems individually or in combination, in order to indicate what is environmentally acceptable for different technologies and scenarios.

Ultimately, the aim is to give a recommendation for the design of specific urban energy system configuration, one that is not economics-oriented, but rather places an emphasis on environmental impact. In the following sections, one hopes to highlight some of the practical issues associated with these methods, such as the types of data required, the feasibility of obtaining this information, the ease of applying the method, and the technique's general relevance to the study of urban energy systems.

3.3 Material Flow Analysis

Material Flow Analysis (MFA) is defined by the holistic analysis of the inputs and outputs of process sequences, including material extraction or harvest, chemical transformation, manufacturing, consumption, recycling and disposal of materials. This method relies upon accounts, measured in physical units (typically tonnes) that quantify the throughput of such processes. Chemical substances, for example carbon or carbon dioxide, can be accounted for in this way, as well as natural and technical compounds, such as coal and wood. MFA carries a clear resemblance to financial accounting and to traditional economic principles. Despite the fact that there are small differences in approach based on the research questions being tackled, the concepts of an industrial metabolism and mass balancing (i.e.

ensuring that the net mass in and out of a system is zero) become a common foundation for MFA studies.

Policy-makers are becoming more and more familiar with the benefits of MFA and related techniques in their decision-making processes. All of these methods contribute information to the "know-how" of industrial and urban metabolisms. The ideal set-up of a sustainable industrial and urban system is given by consistent and minimized physical exchanges between the environment and human society, with the internal material cycles being driven by renewable energy flows (Richards *et al*., 1994). Having a more sustainable approach to the urban and industrial metabolism is the desired objective of current governments worldwide, which has led to the identification of different ways to achieve this target.

3.3.1 MFA re-named

There are several different "flavours" of material flow analysis and, while the underlying principles are similar, the focus of the study varies as described below.

Substance Flow Analysis (SFA) Studies of the material flow of a specific substance are typically known as substance flow analyses. The substance of interest is often an environmental pollutant like lead, or, in the case of fossil-fuelled energy systems, carbon dioxide. Accounting for carbon dioxide and other greenhouse gases, studying their trends, sources and related technologies, is a particularly popular research and statistical topic.

By determining the main entrance routes of such substances to the environment, understanding the processes associated with their emissions, the flows within the systems in which they exist, and taking into consideration biochemical and physical changes in the environment, one can quantitatively assess risks linked to such substance-specific outcomes.

Life Cycle Assessment (LCA) If the main concern is the environmental impact of a certain product or service, then MFA may be used as a vital step within a wider LCA. The system boundary for an LCA is broad, encompassing all aspects of the anthroposphere, environment, technosphere, or physical economy related to the product in question. More on LCA and its applications on urban energy systems can be found later in this section.

Nevertheless, it must be noted that shifting from single substances to products containing multiple substances, causes an increase in the complexity of the analysis due to additional potential impacts.

Urban metabolism A very significant and increasingly popular domain of MFA is depicting and analysing the metabolism of cities, regions and national or international economies. As mentioned earlier, the distinguishing feature of the urban metabolism approach is its use of a system boundary of direct relevance to a city (rather than a discrete process as in MFA). This type of study is becoming an essential tool for the evaluation of the sustainability status and trends within cities.

To achieve these goals, the strategies of “detoxification” and “dematerialization” of the industrial and urban metabolism are typically adopted. The former refers primarily to pollution reduction, wherein steps are taken to mitigate the releases of particular substances to the environment. These have been primarily controlled using governmental regulations banning certain substances, and additionally by introducing cleaner technologies. Solutions are typically provided to address the needs of specific regions and relatively short-term periods (i.e. years). However, in the case of climate change and greenhouse gas emissions, the drive for long-term and global solutions creates the need to analyse flows of critical substances, materials or products, in a systems-wide approach, incorporating cradle-to-grave techniques.

The second strategy, “dematerialization” relies on the principles of resource efficiency. By controlling the quantity of primary resources “ingested” by the urban and industrial systems, the method aims to tackle the problem at its root. The desire for eco-efficiency includes not only major inputs (e.g. materials, energy, water) but, at the same time, takes into consideration major outputs to the environment (e.g. emissions to air, water, waste) and associates them with the products or services produced (EEA, 1999; OECD, 1998).

MFA highlights the importance of acquiring data about industrial and urban processes. These data collection systems help researchers evaluate the balance of anthropogenic and natural flows in the economy and environment, but also help policy-makers to demonstrate the cost efficiency and effectiveness of their policies. Consequently, a recent review study (Bringezu, 2000) concluded that the results and findings of MFA-related studies have been used and currently are used in environmental protection policies:

- to support public debate on goals and targets, particularly with respect to resource and eco-efficiency matters, and the meshing of environmental and economic policies;
- to compile economy-wide material flow accounts for use in official statistics databases; and
- to progress monitoring through the derivation of sustainability indicators.

3.4 Ecological Footprinting

In the case of energy systems, a key consideration is the linkage between the emissions of carbon dioxide from fossil fuel combustion and its absorption by the biosphere. In other words, how much land is needed to soak up energy-reated greenhouse gas emissions? Although this narrow perspective of the ecological footprint of energy systems is strongly critiqued in Ayres and Ayres (2002), calculations such as the example below, are common (e.g. Barrett *et al*. 2002).

3.4.1 Calculating the ecological footprint of an energy system

The steps involved in calculating the ecological footprint of an energy system, or at least the footprint associated with the greenhouse gas emissions are:

1. *Calculate the greenhouse gas emissions associated with fossil fuel combustion.* Fossil fuels emit different amounts of carbon dioxide for the same energy value. Reference tables, such as Table 1, provide these conversion factors though one must be careful to ensure comparisons are made on a like-for-like basis. Life cycle analyses of fuel production for example can change the final emissions level by 30 to 50 per cent (Barrett *et al.,* 2002).
2. *Calculate the land equivalent needed to absorb the emissions.* Assuming that 1GWh of natural gas was burnt, 184 tonnes of CO_2 would need to be absorbed. This number is then converted into the amount of land required to absorb the CO_2, using reference tables to find that 5.2 tonnes of CO_2 is absorbed by 1 hectare of forest: 184/5.2 = 35.4. Since the ecological footprint works on the concept of a globally average hectare of land, a further conversion factor must be used to express the relative productivity of the land type in question to the world average. In this case, it is assumed that forest is 1.78 times more productive than the global average hectare

and so the ecological footprint can be calculated as: $35.4 \times 1.78 = 63.0$ global hectares (gha).

Table 1: CO_2 emissions created by the direct combustion of different fossil fuels, i.e. Scope 1 emissions, (Emission factors calculated on a Net Calorific Value basis), (Defra, 2011).

Fuel	Conversion factor (kgCO_2 per kWh)
Natural Gas	0.184
Coal	0.325
Oil	0.267
Petrol	0.241

By taking into consideration the total amounts of different energy forms used in an urban energy system and multiplying by the appropriate conversion factors, one can calculate the ecological footprint of energy consumed in a city. This has been done for cities such as London (CIWM, 2002), York (Barrett *et al*., 2002), Santiago de Chile (Wackernagel, 1998), Macao (Lei and Wang, 2003), and for countries such as Australia (Lenzen and Murray, 2001), Sweden (Wackernagel *et al*., 1999), and New Zealand (McDonald and Patterson, 2004).

3.5 Life Cycle Assessment

Life cycle assessment (LCA) is a methodology developed to evaluate the environmental performance of a process, product or activity. It encompasses all stages in a product's life cycle, from natural resource extraction to final product use and disposal and is therefore often known as a "cradle-to grave" analysis. The main stages of the LCA, as defined by the Society of Environmental Toxicology and Chemistry (Consoli *et al*., 1994) are:

1. Define the goal and scope of the analysis, including the system boundaries;
2. Compile an inventory of materials and energy use and of emissions and solid waste, known collectively as "burdens", associated with the product or service;
3. Assess the impact of the burdens, with the following steps:
   - Classification, in which the burdens are aggregated into a smaller number of environmental impacts;
   - Characterization, where the potential environmental impacts are quantified;
   - Valuation, by which the environmental impacts are reduced to a single measure of environmental performance;
4. Identify steps to reduce the product's environmental impacts.

One of the more recently developed methods of life cycle analysis is the Eco-Indicator 99 Methodology published by PRé Consultants (2001). It has been used to calculate the environmental impact of a large number of commonly used materials and processes. The technique attempts to model the potential damages of a product or service in three damage categories or "endpoints". These are:

- Human health – All human beings, in present and future, should be free from environmentally transmitted illnesses, disabilities or premature deaths;
- Ecosystem quality – Non-human species should not suffer from disruptive changes of their populations and geographical distribution;
- Resources – The nature's supply of non-living goods, which are essential to human society, should be available also for future generations.

Four steps are taken to arrive at a value for a particular process (Pre Consultants, 2001) and the method is summarized graphically in Figure 15.

1. The *Resource*, *Land-use and Fate Analysis* step, in which the fate of emissions and the extraction of resources is analysed based on emissions inventories and feedstock requirements.
2. The *Exposure and Effect Analysis* step, to determine how much of a substance released into the environment is actually taken in by living life forms, such as plants, animals and humans. The effect that resource extraction has on future generations is also analysed at this stage. The result is the classification of the impacts according to twelve indicators such as climate change, ozone layer depletion, acidification and eco-toxicity.

3. The *Damage Analysis* step quantifies the impact of each category by using a damage factor and the twelve indicators are then aggregated to form the main three damage categories mentioned earlier.
4. The *Normalization and Weighting* step, in which a single aggregated Eco-Indicator 99 value s calculated through normalization and by assigning scores and relative weighting factors to each impact category. The assignment of relative importance is a subjective exercise, hence the methodology provides three different "perspectives" based upon the principles of the cultural theory of risk.

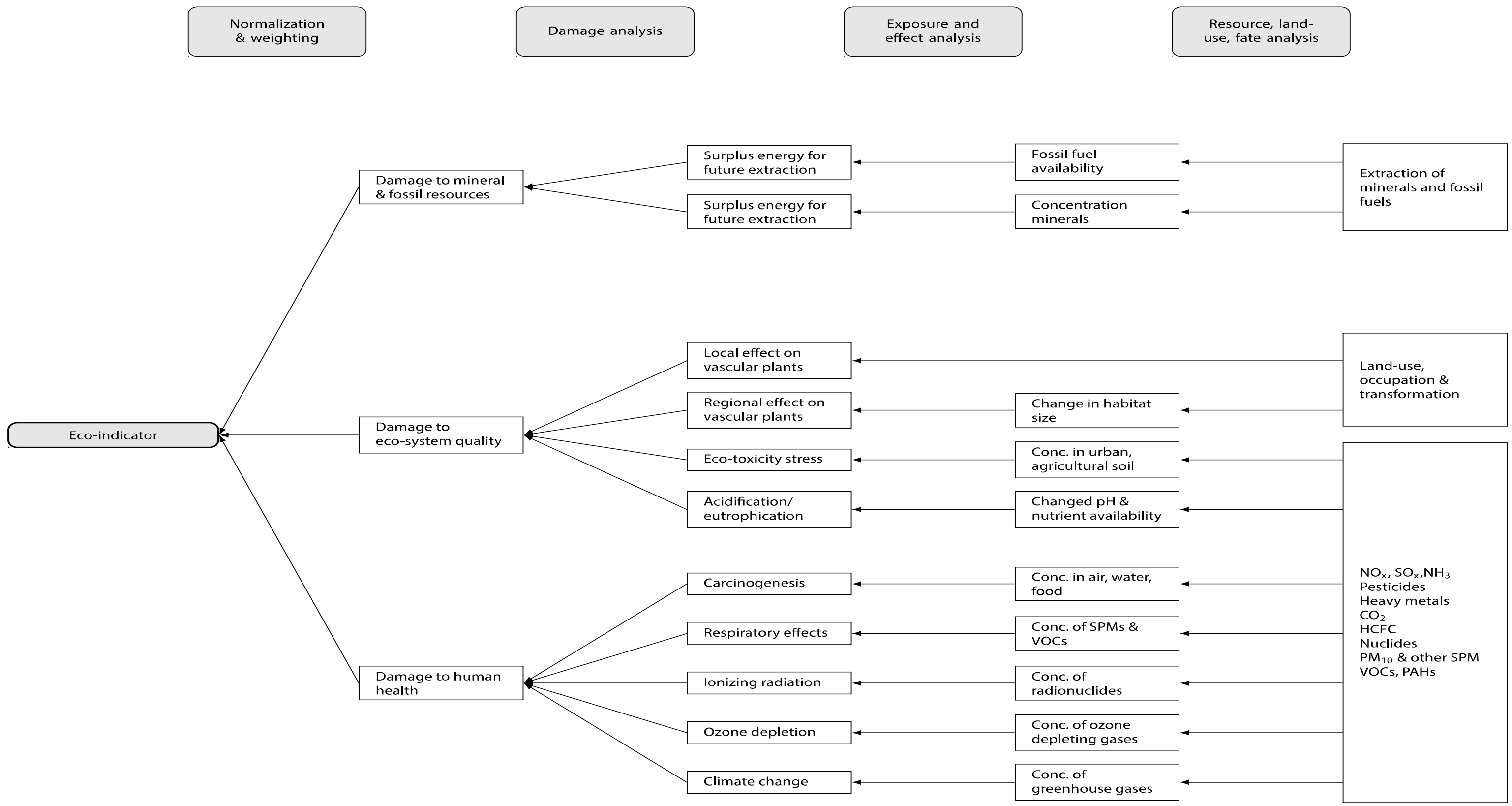

Figure 15: The Eco-Indicator 99 methodology (Pre Consultants, 2001). SPM = suspended particulate matter, VOC = volatile organic compoun, PAH = polycyclic aromatic hydrocarbons, HCFC = hydrofluorocarbons.

3.5.1 Cultural theory of risk and LCA

The cultural theory of risk (see Thompson *et al*., 1990) is based on the type of relations that people have within a group and how an individual's life has been moulded by external events, otherwise known as their "grid". The assumption is that the position of each individual in this group-grid setup has a large influence on the value system of individuals and their groups. Hence, these value systems are used frequently to tackle the problem of modelling subjectivity. The five most important archetypes that have been identified to generally explain people's attitudes are:

1. *Individualists*, who are relatively free of control by others, yet are often engaged in controlling others.
2. *Egalitarians*, who portray no character differentiation, and relations between group members tend to be ambiguous, causing conflicts.
3. *Hierarchists*, who are both controlling others, but are also subject to control by them, bringing a sense of stability to the group.
4. *Fatalists*, who act alone, lack opinion and are typically controlled by others.
5. *Autonomists*, who are usually the smallest group that manages to escape any manipulative forces from the rest and think completely independently.

The representatives of the first three archetypes are often the most useful in decision-making, since the have such different opinions between them, whereas the last two categories represent a smaller range of perspectives.

Based on these three personality profiles, Hofstetter (1998) stated that three versions of an LCA could be produced:

1. The individualist version, where only proven cause-effect relations are included and short-term perspectives are chosen. For example, in human health issues, age-weighting is used, due to the individualist's typically higher proportion of ages 20-40.
2. The hierarchical version, where facts from recognized scientific and political bodies are included. A classic example is the accordance with the IPCC climate change guidelines
3. The egalitarian version, where the largest amount of data is included, with little omissions and long-term perspectives, since this version is of a precautionary nature and does not ignore possible future problems.

Consequently, following the completion of an LCA, three possible scores can be obtained, depending on the cultural theory perspective. The hierarchical version is usually the default method since its ideology is most common in the scientific community and in political organizations. The other two methods can provide basis for sensitivity analyses if desirable. Therefore, the final weighting is heavily determined by the basic value system a person is using and the concepts of cultural theory of risk play a large role in its derivation.

The Eco-Indicator 99 Methodology is considered advantageous over other techniques due to its systematic ideology which produces a single value that is representative of all the different environmental concerns. Equally important is the fact that the calculations can be 'interrupted' at any stage according to the particular needs of the impact assessment (Hugo *et al.* , 2004).

3.6 A hypothetical case study

In order to illustrate the way in which LCA and urban energy systems modelling can fuse, a hypothetical case study was devised for an area of 980 hectares (divided into 49 cells with 20 ha area each). The purpose is to show potential energy technology combinations and reductions in environmental impact achieved through scenario planning and integrated design.

The model for the hypothetical case study was built using the mixed-integer programming methodology. It includes various technologies, resources and products and was run to select the least environmentally harmful combination, by minimizing one damage category at a time. The model is presented in this section, primarily by stating the main assumptions and the mathematical formulation. As the equations are linear and include binary and continuous variables, he problem is classed as an MILP and can be solved using GAMS/CPLEX.

3.6.1 Model Notation and Formulation

The model is formulated as follows; Definitions of the symbols can be found in this section.

SETS

R = Set of resources, $r \in R$

EI_r = Set of environmental impacts, $ei_r \in EI_r$

Nr_r = Set of non-accumulating resources, $nr_r \in Nr_r$

T = Set of technologies, $t \in T$

G_t = Set of technologies that import resources, $g_t \in G_t$

P_t = Set of technologies that consume resources, $p_t \in P_t$

VARIABLES

$Q_{r,i,i'}$ = Flow of r from i to i'

$P_{r,i}$ = Production of r in cell i

$\mathrm{T}_{t,i}$ = Production rate of t in i

$A_{r,i}$ = Accumulation of r in i

CAP = Capital cost per annum

ENV = Environmental impact

Z = Objective function

PARAMETERS

$TechCC_t$ = Technology capital cost (k£)

$TechCap_t$ = Technology capacity in kW

$RCost_r$ = Impact value of each resource

$D_{r,i}$ = Demand of each resource in each cell

$TransCC_r$ = Transportation capital cost of r per m

$MaxTrans_r$ = Maximum rate of transport for resource r

XC_i = X co-ordinate of i

YC_i = Y co-ordinate of i

$distance_{i,i'}$ = Distance from i to i'

$ConvFct_{t,r}$ = Rate of *r* produced per rate of operation of *t*

BINARY VARIABLES

$X_{r,i,i'}$ = If network exists for *i* between *i* and *i'*

INTEGER VARIABLES

$N_{t,i}$ = Number of *t* at *i*

First, the set of resources included in the model is given by $r \in R := \{\mathrm{Re}source1, \mathrm{Re}source2, \mathrm{Re}source3, \ldots\}$. Some of the resources are used as feeds to the technologies (e.g. natural gas), whereas others are also considered as products (e.g. electricity). Environmental impacts (e.g. global warming potential) were also seen as exiting "resources" from these technologies, in order to facilitate the formulation of the model. The resources were further sub-divided into accumulating (i.e. all waste and environmental impacts) and non-accumulating.

The set of technologies was given by $t \in T := \{Techno\log y1, Techno\log y2, Techno\log y3, \ldots\}$ .These technologies were sub-divided into technologies that import resources (e.g. electricity grid) and those that consume resources (e.g. a natural gas boiler).

A resource balance is defined for each cell, denoting resources coming in from outside the cell, plus those produced locally, minus the demand, minus those leaving the city and must equal to accumulation:

$$\sum_{i'} Q_{r,i,i'} + P_{r,i} - D_{r,i} - \sum Q_{r,i,i'} = A_{r,i} \qquad \forall r,i \quad (3.11)$$

But accumulation must be zero (unless the resource is an environmental impact or waste):

$$A_{r,i} \leq 0 \qquad (3.12)$$

The production rate of resource *r*, in cell *i*, is given by:

$$P_{r,i} = \sum_{t} \tau_{t,i} * ConvFct_{t,r} \qquad (3.13)$$

Where $ConvFct_{t,r}$ is a conversion factor for a given technology and resource, and τ is the production rate of technology *t*, in cell *i*, given by:

$$\tau_{t,i} \leq N_{t,i} * TechCap_{t} \qquad (3.14)$$

$$\tau_{t,i} \geq 0 \qquad (3.15)$$

The flow of resources between the cells can be described by the following equations:

$$Q_{r,i,i'} \leq X_{r,i,i'} * MaxTrans_r \qquad (3.16)$$

$$Q_{r,i,i'} \geq 0 \qquad (3.17)$$

The capital cost can be defined in terms of the technology capital costs and the transportation capital costs as shown below. Similar terms could be introduced to capture the operating and maintenance costs but are not shown here for clarity.

$$CapitalCost = \sum_{r,i} TechCC_t * N_{t,i} + \sum_{r,i,i'} TransCC_r * X_{r,i,i'} * distance_{i,i'} \qquad (3.18)$$

The environmental impact can therefore be defined as the cost of each resource multiplied by the resource accumulation in a cell and is given by:

$$EnvironmentalImpact = \sum_{r,i} RCost_r * A_{r,i} \qquad (3.19)$$

Recalling that we are only interested in the environmental impact for this study, the objective function Z can be defined as shown below. Total financial costs could also be incorporated into this objective function if desired.

$$Minimize \qquad Z = EnvironmentalImpact \qquad (3.20)$$

4. RESULTS AND ANALYSIS

4.1 Input data and assumptions

The model begins by specifying the final energy service requirements of the city. The demands for heat and electricity for this fictional area were estimated on a per-capita basis to suit the needs of this case study. The algorithm generates random values for each cell by assuming high demands in the central cells, or otherwise "city-centre", and decreasing demands as one proceeds to the outskirts. For each cell, it is assumed that the demand for heat and electricity can be generated locally otherwise resource flows take place between cells, as long as a feasible route exists.

A number of energy conversion technologies are then used to convert between raw input fuels and final energy services. Each technology has a series of parameters giving their capital cost, operating costs, and resource efficiency, as shown in Table 2.

Table 2: Energy technologies and their approximate capacities based on author estimates. O&M = operating and maintenance costs.

Technology	Capacity (kW)	Efficiency (%)	Capital cost (£)	O&M cost (£)
Biomass CHP	45000	80	35 million	3 million
Biomass Boiler	2	90	600	50
Coal CHP	45000	70	15 million	0.5 million
Electricity grid	45000	0.033 per km	80,000 per km	900 per km
Natural Gas grid	100	Negligible	150,000 per km	2,500 per km
Natural Gas CHP	1500	70	1,000,000	35,000
Natural Gas Boiler	1	90	850	50

Since minimizing the cost of the energy system configuration is not of primary interest here, the values shown in the table are estimates. Indeed costs are completely omitted from the objective function for the present case study so that only environmental impact affects the results. However, if economic considerations become of interest at a later stage, the model can be modified, for example using the constraint method to pursue a multi-objective optimization (e.g. minimizing costs subject to limits on environmental impact, or minimizing environmental impact subject to cost constraints). The constraint value can be modified and the model re-run to generate multiple solutions and thereby explore the interaction between the economic and environmental objectives.

4.2 Optimization results

The model was run under three different scenarios for minimizing different kinds of environmental impact, as listed below:

- Scenario 1: The objective function was to minimize Global Warming Potential (GWP);
- Scenario 2: The objective function was to minimize Resource Depletion (RD); and
- Scenario 3: The objective function was to minimize Air Quality (AQ).

For each scenario, the results were calculated for all three environmental impact metrics and these are shown n Table 3:

Table 3: Changes in environmental impact values when minimizing one objective at a time.

Objective function (minimize …)	Output metric Global Warming Potential ($kg\ CO_{2_{eq}}$/hr)	Air Quality (10^{-9} DALY/J)	Resource Depletion (kW)
Global Warming Potential	*489*	119	221
Air Quality	3,460	*81*	2,150
Resource Depletion	4,940	498	*182*

DALY = Disability Adjusted Life Years, and therefore DALY/J = DALY/kg (of harmful substace exposed to) × kg (of harmful substance released)/TJ (of natural gas burnt) = 10^{-9} DALY/J.

It can be observed that when the objective is to minimize air quality, the values of GWP and RD increase by seven times and approximately twelve times against their optimised values, respectively. Similarly, when resource depletion is chosen as the objective to be minimized, a ten-fold increase is seen for GWP and a six-fold increase in the value of AQ. However, when global warming potential is chosen to be minimized, the AQ value is only around 30 per cent away from the minimum value which can be achieved when air quality is the objective. Similarly, for resource depletion, the obtained value when GWP is minimized is less than 20per cent from the equivalent achieved when minimization of resource depletion is the objective. It therefore seems that out of the three environmental impacts, minimization of GWP affects the optimal values of the other two categories the least.

4.3 LCA-based Scenario Analysis

For each scenario, the model also provides the choice of technologies which led to least environmental impact according to the damage category of interest. The values in Table 4 represent the relative contribution of each selected technology to total urban energy demand.

Table 4: The model's choice of technologies according to environmental impact. Values indicate the per cent of total urban energy demand satisfied by a given technology. CHP = combined heat and power.

	Objective function (minimize …)		
Technology	Global Warming Potential	Resource Depletion	Air Quality
Biomass CHP	48	–	–
Biomass boiler	52	52	–
Coal CHP	–	48	–
Gas CHP	–	–	48
Gas boiler	–	–	52

To achieve the best results in terms of GWP, the model chose only the biomass technologies, whereas for RD, it found that a combination of biomass and coal is better to use as resources. On the other hand, when AQ was the objective, all natural gas technologies were preferred. The results agree with what was perhaps to be expected, i.e. biomass technologies tend to have low carbon dioxide emissions which is considered a significant contributor to global warming. Furthermore, coal is still abundant in comparison to natural gas reserves and so is biomass, so if resource depletion minimization is the objective, then natural gas technologies would not constitute a satisfying solution. Finally, in terms of air quality, all natural gas technologies were chosen by the model to satisfy the electricity and heat demands, since very little particulate emissions occur from them.

These results point back to the issue of how different stakeholders might define “environmental impact”. Each country, government, community and industry will have its own priorities with respect to which environmental impact is to be minimized. But as can be seen, the choice of one objective tends to hinder the others and some view will need to be taken on whether, for example, air quality or global warming potential is more important.

However, one can say that in order to achieve minimum environmental impact, different system designs need to be considered and incorporated in an urban area. An optimum combination of energy technologies based on demand and geographical considerations could possibly satisfy the minimum environmental impact objective. Of course, the issue becomes even more interesting and complex when cost is introduced as a more significant component to the objective function. LCA may prove to overcome the hurdles of other environmental assessment methods by providing a link between the environmental impacts and the economics of an urban energy system.

4.4 Selecting EIA methodologies for UES design

Generally, optimization techniques are applied to a problem or case study as a final step in the process of its analysis and understanding. Optimization results typically provide quantitative improvement with respect to a system's initial state. However, what about taking one step back, and analyzing the system in question in a rather qualitative manner, to see what can possibly be revealed prior to any quantitative improvements?

To demonstrate this ideology, a real case study is introduced and put through environmental impact assessment methodologies. By performing this step, one can obtain more qualitative information. Specifically, this can show which EIA methodology (or combination of them) is most relevant and appropriate to the design of a particular urban energy system and how readily it can be applied.

4.5 Scenario Analysis

Three different methods of measuring environmental "friendliness" have been analyzed and applied to a UK eco-town. These methodologies can be applied to an urban energy system individually or in combinations to indicate what is environmentally acceptable for different UES solutions and scenarios.

As mentioned earlier in this report, the case study is a proposed eco-town in England with an estimated population of 6500 and an overall energy demand of 273 GWh/year, split into 188 GWh of heat demand and 75 GWh of electricity demand. Five different energy system scenarios were taken into consideration and compared with respect to the three EIA methodologies: MFA, LCA and EF.

- Scenario A: Natural Gas & Electricity Grid (base case)
- Scenario B: Natural Gas only
- Scenario C: Biomass (Combination of Electricity Grid & Biomass CHP)
- Scenario D: Waste-to-Energy (Combination of Anaerobic Digestion, Electricity Grid & Natural Gas)
- Scenario E: Mixed Renewables (Combination of PV Cells, Wind Turbines, Heat Pumps, Electricity Grid & Natural Gas)

For the purposes of all scenarios, it was assumed that the UK electricity grid constitutes a mix of 43.5 per cent natural gas, 33 per cent coal, 16.1 per cent nuclear and the remaining 7.4 per cent representing other fuels (BERR, 2005). For the biomass scenario (scenario C), it was assumed that 33 per cent of the electricity demand comes from a biomass CHP, whereas for the waste to energy scenario

(scenario D), it was assumed that 20 per cent of the total energy demand can be produced by the anaerobic digestion of municipal solid waste. For the mixed renewables scenario (scenario E), it was assumed that 10 per cent of the electricity demand comes from renewable technologies (i.e. PV cells and wind turbines) and 10 per cent of the heat demand is also produced by renewable technologies (i.e. heat pumps and solar thermal collectors).

In order to calculate the amount of each fuel needed to run the UK eco-town and thus obtain values for the material flow analysis, the heat and electricity demands for each scenario (comprised by the relevant fuel fractions as mentioned in the assumptions) were divided by the calorific value of each fuel. The calorific values used can be found in Appendix B.

Table 5 shows the results of the material flow analysis, indicating how much of each fuel (natural gas, coal and biomass) is required for the smooth operation of each energy system scenario. All materials are reported in tonnes and give an idea of how sustainable (or not) each technology is. The major component of each scenario involves natural gas, with the base case (scenario A) and the mixed renewables option (scenario E) requiring the largest amounts of coal. Even though the biomass option (scenario C) requires lower amounts of coal and natural gas, an environmental impact can be associated with the introduction of just over a million tonnes of wood chips to fulfil the end-use energy demand of this eco-town.

Table 5: Material needed to run the UK eco-town based on five different scenarios.

Scenarios		Fuel consumption (tonnes/yr)		
		Natural Gas	Coal	Biomass
A	Natural Gas & Electricity Grid (Base Case)	12,800	7,470	0
B	Natural Gas only	17,900	0	0
C	Biomass (Combination of Electricity Grid & Biomass CHP)	12,800	4,980	6,110
D	Waste to Energy (Combination of Anaerobic Digestion, Electricity Grid & Natural Gas)	10,300	5,980	0
E	Mixed Renewables (Combination of PV Cells, Wind Turbines, Heat Pumps, Electricity Grid & Natural Gas)	11,800	6,640	0

For the purposes of the life cycle analysis, the total flows of each resource required to meet the energy demands of the UK eco-town were further multiplied by a greenhouse gas emission factor. In this manner, the flows were converted to environmental impact, i.e. quantifying the total greenhouse gases emitted per person.

Based on the results of section 4.1, it has been concluded that out of the three environmental impacts, namely, air quality, resource depletion and global warming potential (GWP), the minimization of GWP affects the optimal values of the remaining two categories the least. GWP is the factor with the greatest impact on a system and therefore the LCA is conducted on a greenhouse gas (GHG) emissions basis in this case. Subsequently, the energy systems were compared with respect to their GHG emissions per capita as shown in Figure 16. It appears at the waste-to-energy option (scenario D) achieves the lowest GHG emissions per year, whereas the base case, i.e., using the combination of natural gas for heating purposes and the grid for electricity demands seems to score the highest.

An ecological footprint analysis (measuring how much area of biologically productive land and water an individual, population or activity requires to produce all the resources it consumes and to absorb the waste it generates, using prevailing technology and resource management practices - measured in global hectares) was also performed. For all five scenarios it was assumed that 150 hectares of productive land are required to produce 1 GWh of electricity and 65 hectares of productive land are required to produce 1 GWh from gas for heating purposes. Additionally, it was assumed that 15 tonnes of biomass are required per hectare for the biomass scenario (scenario C), as well as 400 tonnes of municipal solid waste per hectare for the waste to energy scenario (scenario D). For the mixed renewables scenario (scenario E), it was assumed that 24 hectares of productive land are required to produce 1 GWh from PV cells, whereas 6 hectares of productive land are required for producing 1 GWh from a wind turbine. A zero emission factor was assumed for producing heat from renewable energy technologies. By multiplying these factors with the energy demands accordingly, the ecological footprint for each scenario can be obtained.

Since the system under study is an energy system, the primary environmental impact is the greenhouse gas emissions and therefore, the comparison of energy systems based on ecological footprint follows closely the pattern of the LCA study. However, the lowest ecological footprint is achieved by scenario B this time, the natural gas only set-up.

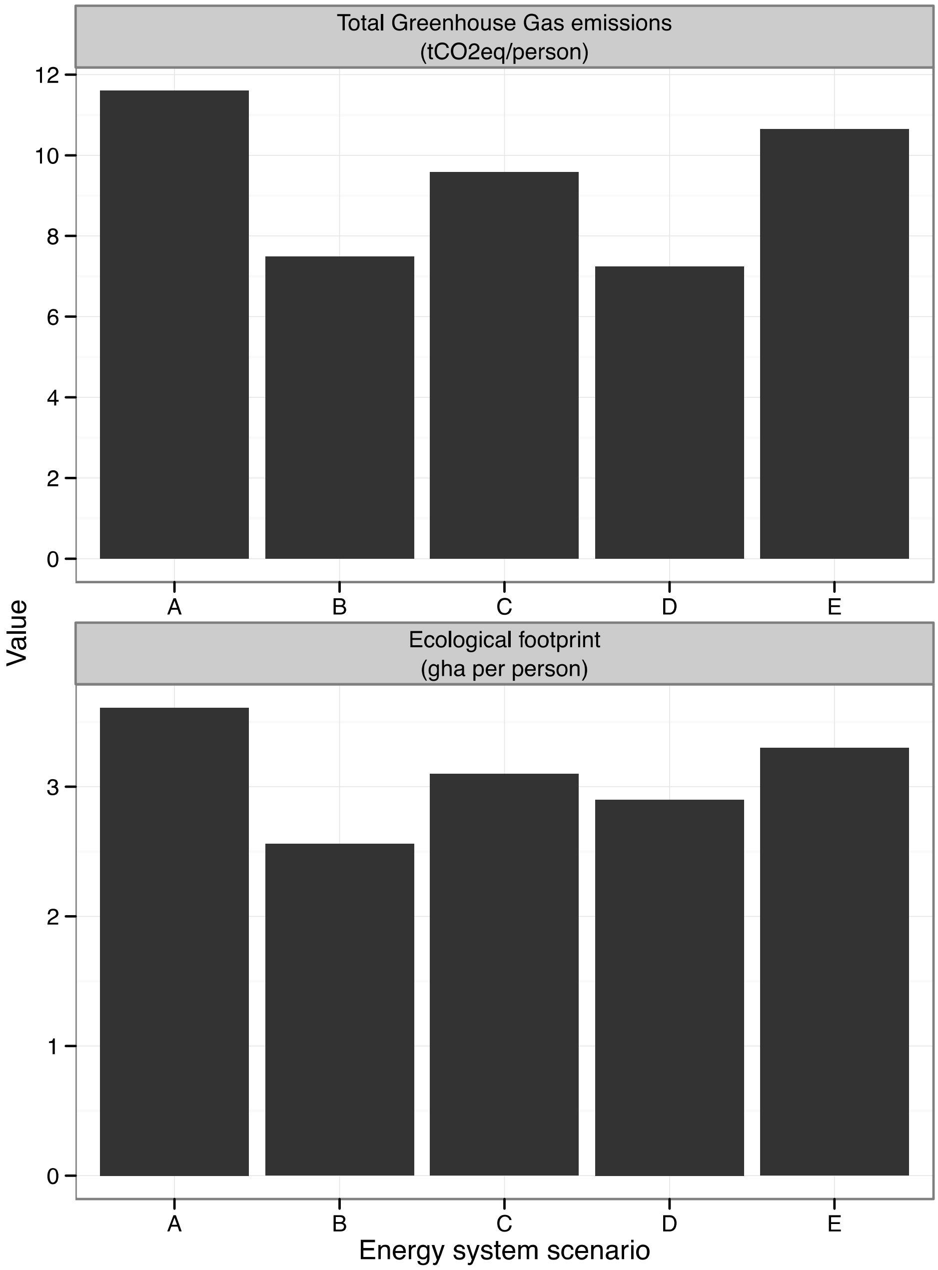

Figure 16: The relative environmental impact of urban energy systems of a UK eco-town based on greenhouse gas emissions per capita (LCA) and ecological footprint per capita.

Following the UK eco-town case study, it was decided to apply the same techniques to a larger, more complex energy system, like the one of the city of Toronto, Canada. Toronto is home to 2.6 million inhabitants and has an energy demand of 72,535 GWh per year. This overall energy demand is sub-divided to 29,878 GWh of electricity demand and 42,657 GWh of heat demand.

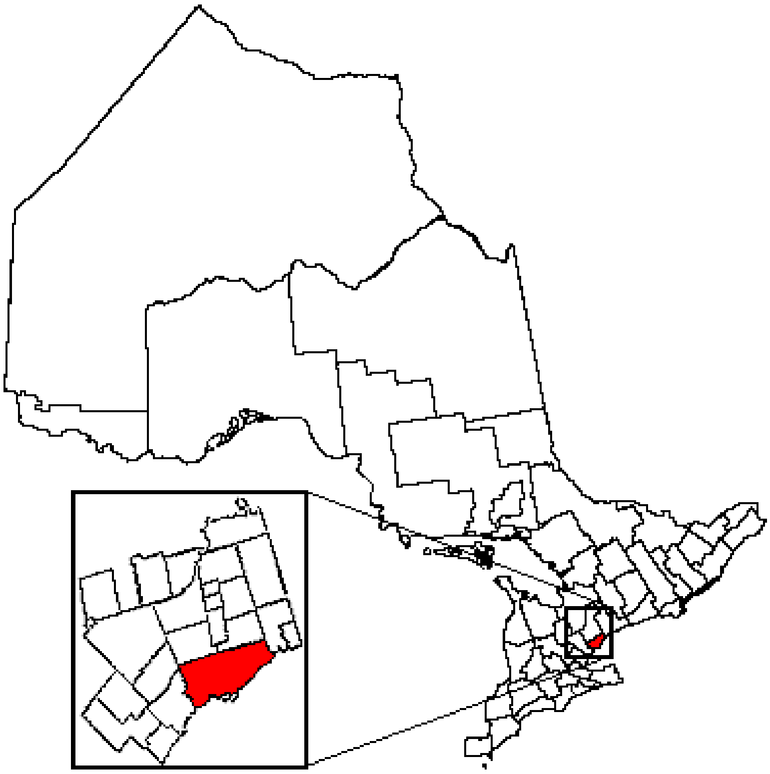

Figure 17: Location of Toronto and its census metropolitan area in the province of Ontario (Wikipedia, 2012).

The same assumptions were used for the Toronto case study as for the UK eco-town case study in the majority of the model. The only difference was the composition of the electricity grid. The Canadian grid contains a mix of 6.6 per cent natural gas, 16.6 per cent coal, 15.5 per cent nuclear and the remaining 61.3 per cent other sources such as hydroelectricity.

The five different energy scenarios were re-applied and Table 6 shows the material flow analysis for the city of Toronto, indicating how much of each fuel (natural gas, coal and biomass) is required for the smooth operation of each energy system scenario. All materials are reported in tonnes again and give an idea of how sustainable (or not) each technology is. The major component of each scenario involves natural gas, with the base case (scenario A) and the mixed renewables option (scenario E) requiring the largest amounts of coal. Even though the biomass option (scenario C) requires lower amounts of coal, an environmental impact can be associated with the introduction of more than 500 million tonnes of wood chips to fulfil the end-use energy demand of this eco-town.

Table 6: Material needed to run the city of Toronto based on five different scenarios.

		Fuel Consumption (tonnes/year)		
Scenarios		Natural Gas	Coal	Biomass
A	Natural Gas & Electricity Grid (Base Case)	8,110,000,000	3,570,000,000	0
B	Natural Gas only	13,800,000,000	0	0
C	Biomass (Combination of Electricity Grid & Biomass CHP)	8,110,000,000	2,380,000,000	528,000,000
D	Waste to Energy (Combination of Anaerobic Digestion, Electricity Grid & Natural Gas)	6,490,000,000	2,860,000,000	0
E	Mixed Renewables (Combination of PV Cells, Wind Turbines, Heat Pumps, Electricity Grid & Natural Gas)	8,070,000,000	3,560,000,000	0

The MFA was followed by an LCA in total greenhouse gas emissions and an ecological footprint analysis.

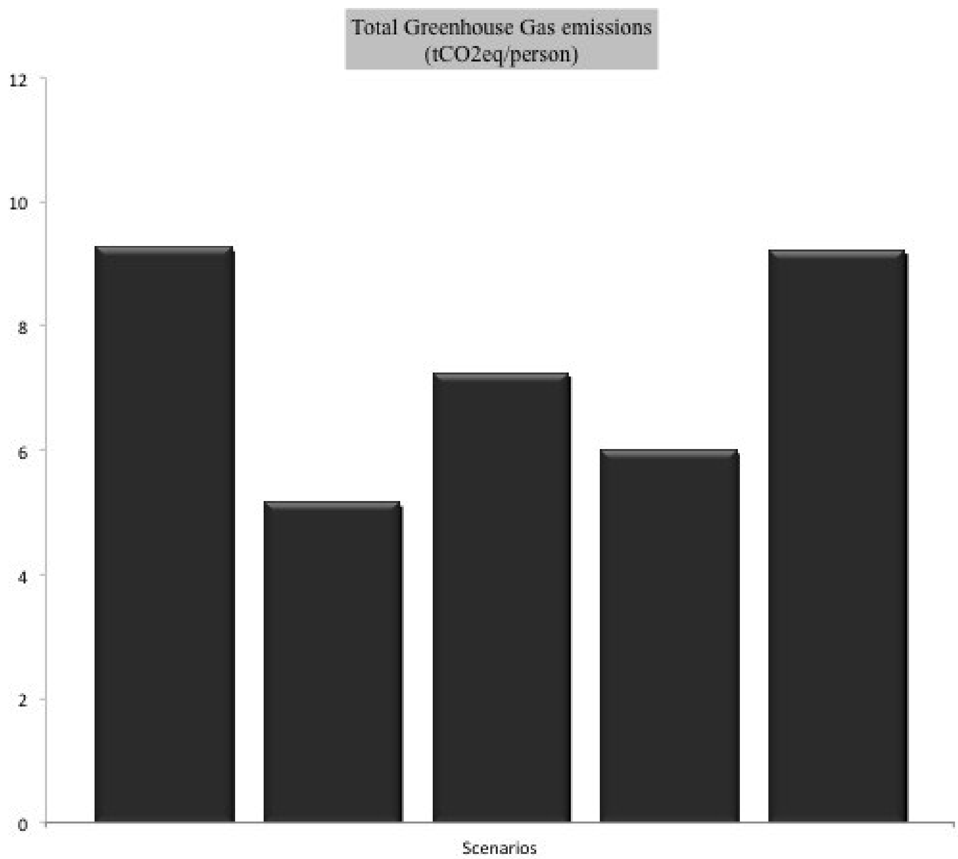

Figure 18: Total Greenhouse gas emissions for the city of Toronto

The energy systems scenarios were compared with respect to their GHG emissions per capita as shown in Figure 18. It appears that the only natural gas option (scenario B) achieves the lowest GHG emissions per year, whereas the base case, i.e., using the combination of natural gas for heating purposes and the grid for electricity demands seems to score the highest.

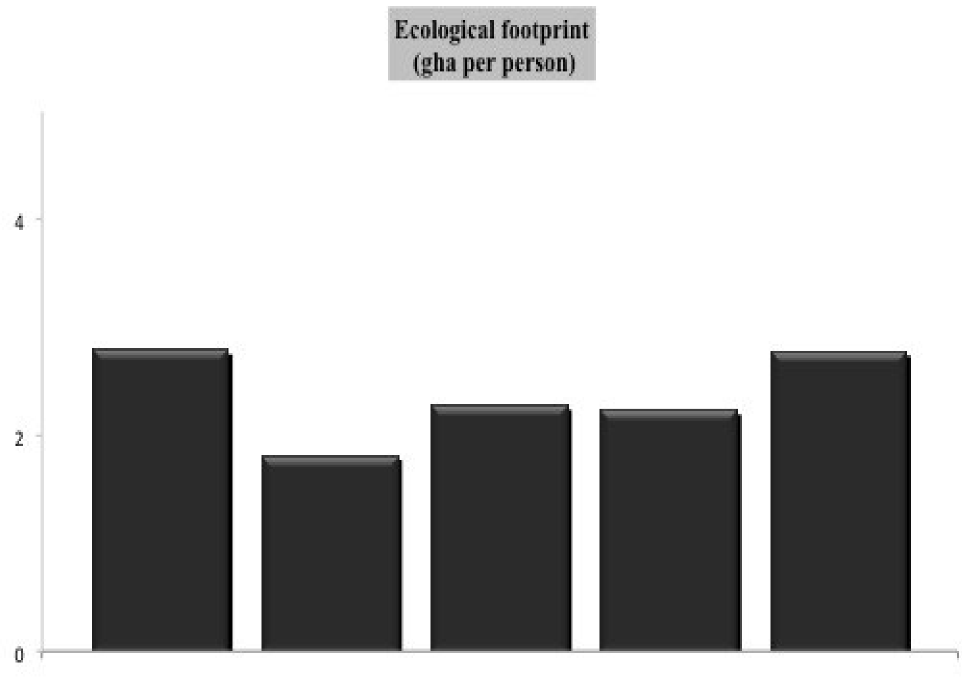

Figure 19: The ecological footprint for each energy scenario for the city of Toronto

The comparison of energy systems scenarios for Toronto based on ecological footprint follows closely the pattern of the LCA study. Again, the lowest ecological footprint is achieved by scenario B, the natural gas only set-up.

5. DISCUSSION

The majority of stakeholders concerned argue that using a single environmental impact assessment methodology to evaluate the sustainability of cities is informative to the decision-makers involved. Nevertheless, the mode in which these techniques are currently applied is helpful to specific urban issues and does not really provide an integrated and insightful measure of urban sustainability as a whole. The dynamic relationship between the society, the economy and the environment affects a city's sustainability to a great extent. The combination of environmental impact assessment methodologies used in this study presents matters from an energy systems point of view and facilitates the choice and interpretation of the outcomes. The more these techniques are combined, e.g. MFA, LCA and EF, the more they help to give a more specific idea of a system's performance, while enhancing the output from existing studies.

The initial objectives that were set for the successful completion of this project have been satisfied in their majority to the best possible outcome, given the timeframe. A mathematical model for a hypothetical urban energy system was formulated, which included various energy technologies, resources and products. The model was run to select the least environmentally harmful combination of energy technologies, by minimizing one damage category at a time. Damage categories included global warming potential, resource depletion and air quality. Additionally, focus was given on environmental impact assessment methodologies such as material flow analysis, life cycle assessment and ecological footprint. These methods were applied on a UK eco-town and on the city of Toronto to provide further insight to urban energy systems. Taking the above into consideration, one can say that the original aims have been satisfied.

The broader context of the results and outcomes, the strengths or limitations of the employed approaches, are discussed on an individual basis in the following sub-sections:

5.1 Life cycle assessment

Many researchers recognize the benefits of LCA as a tool to analyze commensurable features of quantifiable systems. Nevertheless, not all factors can be brought down to a single number and used in a model. The need for solid boundaries makes the accounting of changes within a system, difficult. Furthermore, the availability and accuracy of the data can also add to inaccuracy (e.g. data may be based on averages, samples may not be representative or certain results may be outdated). In the case of LCA applied to energy technologies, one can rename the process to dynamic life cycle assessment. For example, the growing nature of a power grid must be taken into consideration, since a specific type of energy technology may emit more carbon dioxide over its lifetime, than it mitigates. All energy technologies that are trying to give a solution to the challenge of simultaneously satisfying energy demands, while reducing carbon emissions, are responsible for some greenhouse gas emissions during their construction. As these energy technologies expand rapidly, it is essential to provide policy-makers with standardized information in order to achieve climate change mitigation.

5.2 SimaPro software

SimaPro software was used to obtain LCA data for the initial stages of this research project. The software brings together inventory data from a wide range of industrial and economic sectors. Since the inventories are process-based, a user does not need to determine emissions data for basic inputs, such as electricity use, but instead can use already available information to simplify an analysis. The already integrated Eco-Indicator 99 impact assessment tool provides the additional correlation between inventory data and environmental impacts. Even though this software is applicable to any process and it is relatively transparent, it can also be characterized as expensive, labor-intensive and perhaps, containing certain inconsistencies between the different modules containing the process-based inventory data.

5.3 Material flow analysis

Despite its undisputable usefulness, certain shortcomings and limits can be identidied for the standard MFA method. Usually large material flows take dominance over all indicators and affect the interpretation of aggregated results. If only one material category dominates the MFA, it can lead to biased results by ignoring other material groups or economic sectors. Ideally MFA should be carried out at a level that disaggegates economic sectors or material groups. In terms of environmental impacts, by concluding that the reduction of resource use is necessary, it does not mean that it is the only precondition for achieving environmental sustainability. The question would still remain as to which flow has to be reduced to reach a sustainable resource throughput. Additionally, small material flows, which might not be taken into account, can potentially have large environmental impacts. An internationally standardized procedure for considering qualitative changes in the quantitative nature of MFA is at the moment missing. Finally, it would be very beneficial if MFA studies did not only focus on the presentation of material balances, but to further reflect on likely policy-related uses of results.

5.4 Urban metabolism

The concept of urban metabolism is a multi-disciplinary way of characterising the functions within an urban area. Each interpretation has something to offer; MFAs and urban ecology analyses contribute knowledge that can feed into social and environmental policy for urban areas. By portraying an urban area as an ecological system with its own metabolism, it becomes easier to pinpoint the impact of human activity on the natural environment. Additionally, interpretations of an urban metabolism can be made from an ecological economics point of view, calling attention to the environmental and social resources needed to maintain economic growth. Despite the cross-disciplinary appeal that urban metabolism has, there does not seem to be enough interdisciplinary engagement in such studies. Undoubtedly, it would be beneficial to work across disciplines (i.e. integrate industrial and urban ecology processes with social and political factors), in order to offer the possibility of new insights, thus increasing the importance of a wealthy and quickly evolving field of research on the metabolisms of urban areas.

5.5 Ecological Footprints

Generally, the obvious benefit of ecological footprint analysis is its simplicity, since it becomes a type of indicator that anyone can comprehend. As Wackernagel and Rees (1996: 230) reasonably observe, "individuals can contrast their personal footprints with their ecological 'fair Earthshares', national footprints can be compared to domestic territories, and the aggregate human footprint can be compared to the productive capacity of the entire planet." The resulting concept of "ecological deficit", further gives an idea of what a nation's policy target should be. However, given that footprint analysis is not dynamic modelling and lacks predictive capability, many have hinted that this concept is too simplistic. Both nature and the economy are dynamic systems and it is true that this model does not take full account of the sustainability story. For example, only the energy consumption is taken into consideration which confirms the presence of underestimates of the actual ecosystem appropriations. This means that when the holistic picture of consumption processes is included in the analyses, the resulting ecological footprints will be much larger than the current values.

The ecological footprint still forms a significant contribution though. It remains an estimate of how much energy consumption needs to be reduced, technology needs to be improved and behaviour needs to be changed to achieve sustainability. The above limitations do not really detract from the fundamental message of ecological footprint analysis. As Wackernagel and Rees (1996: 232) further note, "Whatever the distribution of power or wealth, society will ultimately have to deal with the growing global ecological debt".

5.6 Simplistic Approach

As witnessed through the course of this work, biophysical models require an extensive amount of very specific data in order to portray accurately the flows of the system under study. Yet, for the sake of simplicity, the standard values available were used.

As a result, the analyses were subject to an amount of assumptions and simplifications, and the overall assessment is also accompanied by uncertainties.

Thus, the approaches could be characterised as reductionistic or simplistic, but one can say that this is the point of these environmental impact assessment methodologies. The tools used in assessing an urban energy system, still decreased and integrated the numerous issues affecting progress towards mitigating an environmental impact to a smaller set of numbers. The latter is an important tool to policy makers as large volumes of statistics can be summarised into a comprehensive manner accessible to non-experts as well.

5.7 "Which EIA methodology (or combination of methodologies) is most relevant and appropriate to the design of a particular UES and how easily can it be applied"?

By applying a combination of the LCA, MFA and ecological footprint methodologies, a more thorough insight is provided to the dynamic and multi-faceted nature of urban energy systems. It is not easy to decide which single metric is most important over others; that is the task of policy-makers and key stakeholders worldwide. Yet, while there is little doubt that global warming is still a main concern for cities everywhere, the environmental impact assessment methods presented in this research illustrate how a range of impacts on health, resource scarcity, and the local and global environments can be evaluated. It is recommended that all methods used in this research, both optimization and environmental impact assessment techniques, be applied to an urban energy system of interest. It is then up to the stakeholders to prioritise the information revealed, based on social, economic, political and technical criteria.

5.8 What do these results mean to policy-makers?

The approach used for this work might help to identify the key inefficiencies of urban energy systems configurations which would, in their turn, promote the development of new technologies or infrastructures. Hopefully, even if this combination of environmental impact assessment methodologies reveals that the sustainability of a city is not as high as anticipated, decision-makers will not pose significant resistance to their adoption because they still provide valuable insights on the system.

By being a fossil-fuel-dependent country, the UK will also face the consequences of increasing oil prices, since countries and governments are now forced to go after reserves in places that are harder to access, both geologically and politically. Its turn towards natural gas is actually leading UK to commit deeper to fossil fuels for its energy supply, but this resource is also depletable and expensive since it is linked to oil pricing.

High energy prices can affect a number of sectors within the UK economy. What will happen with the increase in numbers and popularity of cheap airlines? How will the tourism be affected? The growth in electricity demand is also of major concern. If better urban, transportation planning and building design is introduced, then perhaps power and energy demand in the UK could be reduced or at least maintained constant. If policy-makers were able to enforce stricter efficiency, conservation and recycling measures, then maybe the UK would be able to reduce energy consumption. For example, buildings could be planned and built in a manner to reduce the requirement of heating and lighting.

Perhaps more emphasis should be put on reducing energy use and introducing more eco-towns with configured set of energy technologies tailored to fit their specifications. A rational, holistic policy which will consider the various warnings and devise a preparation strategy would bring enormous benefits to every country's energy profile.

The fact remains that urban energy systems still have room for improvement. The assumption is that a government must provide the increasing energy supply at any cost, in order to "feed" the unsustainable lifestyle of its population. When changes start taking place, any population could experience significant upgrades in social, environmental and economic aspects of its urban life, reminding the reader that energy does indeed play a pivotal role in a country's overall wellbeing.

6. CONCLUSIONS

Until recently, the optimization of urban energy systems has taken a relatively limited view of environmental impact, focusing largely on greenhouse has emissions. This work has sought to widen that perspective, acknowledging the complex characteristics of urban energy systems that make them stand out with respect to other energy systems and seeking to provide a better understanding of how such systems function and interact with respect to various measures of environmental performance. By evaluating the three different environmental impact assessment methodologies, it was shown how qualitative and quantitative analyis techniques can be used to provide additional insight to an urban energy system at various aspects of its functionality.

Having carried out this research, I was able to conclude that:

- Cities play a determining role in the evolution of the energy sectors worldwide due to their large heat and power demands. Consequently, improving the efficiency of urban energy systems is an increasingly important issue.
- Urban energy systems can be seen as eco-systems and all the processes taking place within them, form an urban metabolism characterized by inputs, outputs, and accumulation of various materials.
- The Synthetic City Toolkit, and particularly the Resource Technology Network component, formed a solid basis for this research and outcomes from this research can complement this component of the toolkit.
- Having studied the work of researchers in the fields of optimization, urban metabolism and life cycle assessment methodologies, a gap was identified in

the research that combines optimization techniques and environmental impact assessment methodologies to evaluate urban energy systems, specifically.

- Data had to be collected from a variety of databases, and software, and numerous assumptions had to be made at different stages of the research to build models both in GAMS and in Excel. In many cases, data was not readily available and a certain amount of uncertainty can be attributed to values used to populate the models.
- Life cycle assessment and urban metabolism can be classified as different types of material flow analysis. On the other hand, the ecological footprint can be seen as a rather different approach to characterize urban energy systems.
- Environmental impact assessment methodologies and optimization techniques can fuse to identify the combination of energy technologies that best meet the heat and electricity demand requirements of an urban energy system, while minimizing a specific environmental damage category at a time.
- By minimizing global warming potential specifically, the remaining two damage categories of air quality and resource depletion deviate the least from their optimal values.
- By performing a material flow analysis and a life cycle assessment, and by calculating the ecological footprint of a UK eco-town and the city of Toronto, it is proven that different information can be deduced through each environmental impact assessment methodology and that each of them provides additional insight to these urban energy systems.
- Water withdrawn specifically for the needs of the energy industries present in the two case studies, can also become a measure of environmental friendliness

and sustainability. Indirect material flows, such as water in energy, should not be neglected when looking at an urban energy system.

- The three environmental impact assessment methodologies used are characterized by both advantages and disadvantages in their ideologies. However, they were chosen as the most suitable for application in this research.
- In order to get a holistic view of the environmental impacts associated with the design of a particular urban energy system, it is recommended to apply all three environmental impact assessment methodologies in combination with optimization techniques. The information obtained can then be filtered according to the needs of the stakeholders interested.
- Further interpretation of the environmental impact assessment methodologies in terms of social and economic factors would prove valuable to policy-makers.

6.1 Recommendations for Future Work

- The technical relevance of the outcomes was to provide further insight to urban energy systems and a combination of approaches, which can, in the future be applied to other similar cities. Cities in developing countries would be particularly interesting to look at, since they could potentially integrate the improved efficiencies inherently, during their expansion.
- It would also be beneficial to formally embed the environmental impact assessment methods into existing urban energy systems tools. By integrating these concepts into urban modeling tools, a more interdisciplinary perspective will be adopted.

- Additionally, it would be useful to ultimately connect the energy flows in an urban area with other resources, such as waste and food.
- If more time had been available to elaborate this study, the optimal values of the decision variables could be shown on a pixelated grid diagram. A graph showing the Q values for the hypothetical case study could provide some interesting information. In this way, information about the location and choice of technologies and capacities could also be provided.
- Furthermore, the results could be shown as spatial distributions in order to demonstrate the advantage of using optimization methodologies (for spatial information generation) over the LCA packages (providing aggregated results).
- Multi-objective optimization work to account for economic optimization of the various scenarios and technology options would give further insight to this study, thus combining both the financial, as well as the environmental aspect for decision-makers. Hence, it would be beneficial to include a total cost for each scenario, if there were no time constraints.
- Ideally, the active engagement of the public in collecting data needed for these studies would facilitate the process majorly. It would be very interesting to involve the inhabitants of the urban energy systems under investigation in choosing priorities.

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8. APPENDICES

8.1 Appendix A – Input data used in the GAMS model

```
$TITLE City Layout 49 cells model
OPTION SOLPRINT = OFF ;
OPTION LIMCOL = 0 ;
OPTION LIMROW = 0 ;
$OFFSYMXREF
$OFFSYMLIST
*
*  MILP formulation for first city layout model

SCALAR
  NCS   number of cells
  ALPHA                          /0/
  AREA      area of each cell in Ha /20/
  LEN       length of each cell in m /400/
  BIGM      large number           /350/ ;

SETS
  row   row index              /1*7/
  col   column index            /1*7/
  i     grid square index       /1*49/
*
* 7 by 7 square
*

  r   resources /'gas', 'elec', 'coal', 'biomass',
               'heat', 'dist_heat', 'waste_heat', 'ghg', 'aq', 'rd'/
  ei(r)       environmental impacts /'ghg', 'aq', 'rd'/
  nr(r) non accumulating /'gas', 'elec', 'coal', 'biomass', 'heat', 'dist_heat'/

  t   technologies /'ele_grid', 'ng_grid', 'coal_imp', 'biomass_imp',
                 'ng_chp', 'ng_boiler', 'coal_chp', 'biomass_chp', 'biomass_boiler',
'heat_ex'/
  g(t)  technologies that import resources /'ele_grid', 'ng_grid', 'coal_imp'/
  p(t)  technologies that consume resources
   ;

  p(t) = NOT(g(t)) ;

ALIAS
  (i, i1),
  (i, i2),
  (r, r1);
```

```
SETS
  rci(row,col,i)       association between i row and col ;
  rci(row,col,i)$(ORD(i) = ORD(col) + (ORD(row)-1)*CARD(col)) = YES ;

NCS = CARD(i) ;

PARAMETERS

TechCC(t) technology capital cost k£
 /ele_grid=1000, ng_grid=100, coal_imp=100, biomass_imp=100,
  ng_chp=1500, ng_boiler=1, coal_chp=2000, biomass_chp=1700, biomass_boiler=2,
heat_ex=0.2/

TechCap(t) technology capacity in kWth or kWe
/ele_grid=45000, ng_grid=45000, coal_imp=45000, biomass_imp=45000,
 ng_chp=45000, ng_boiler=2, coal_chp=45000, biomass_chp=45000,
biomass_boiler=2, heat_ex=2/

RCost (r) cost of each resource

Demand(r, i) demand of each resource in each cell

TransCC (r) transportation capital cost of r per m
/gas=1, elec=1, coal=1, biomass=1, heat=1, dist_heat=200, waste_heat=0, ghg=0,
aq=0, rd=0/

MaxTrans(r) maximum rate of transport for resource r
/gas=1E6, elec=1E6, coal=1E6, biomass=1E6, heat=0, dist_heat=1E6, waste_heat=0,
ghg=0, aq=0, rd=0/

XC (i) x co-ordinate of i
YC (i) y co-ordinate of i
dist (i, i1) distance from i to i1
 ;

LOOP( (row,col),
  LOOP( i$rci(row,col,i),
    YC(i) = ORD(row)*LEN ;
    XC(i) = ORD(col)*LEN ;
  ) ;
) ;

TABLE CF (t, r) 'rate of r produced per rate of operation of t'
            gas    elec   coal   biomass          heat   dist_heat     waste_heat
ghg     aq       rd
ele_grid     0      1      0      0                0      0            0          480
7.93E-2   3.68E-2
ng_grid      1      0      0      0                0      0            0            0       0
0
```

```
coal_imp       0      0      1      0                  0      0            0             0        0
0
biomass_imp    0      0      0      1                  0      0            0             36
9.36E-3   1.30E-1
ng_chp        -2.5    1      0      0                  0      1.5          0            261
5.96E-3   1.63E-1
ng_boiler     -1.1    0      0      0                  1      0            0.1          265
6.58E-3   1.63E-1
coal_chp       0      1     -2.5    0                  0      1.5          0            533
5.08E-2   1.19E-2
biomass_chp    0      1      0     -2.5                0      1.5          0             36
8.51E-3   1.63E-2
biomass_boiler 0      0      0     -1.2                1      0            0.2           36
9.36E-3   1.63E-2
heat_ex        0      0      0      0                  1     -1            0             0      0
0      ;

*
*
==================================================================
===================
* ghg is g/kWh  aq is DALY/TJ  RD is MJ surplus/m3
*
==================================================================
===================
*

* to make the environmental metrics per rate of process, need to multiply by the
* amount of resource consumed (gas, coal, etc.)
CF(p,ei) = CF(p,ei)*SUM( r1$(CF(p,r1) < 0), -CF(p,r1) ) ;
*                        \_ find the resource being consumed by p

Rcost('ghg')=1;

dist(i,i1) = SQRT( SQR(XC(i) - XC(i1)) + SQR(YC(i) - YC(i1)) ) ;

demand('elec','1') = 269206.442117691;
demand('heat','1') = 685352.623462677;
demand('elec','2') = 247891.813755035;
demand('heat','2') = 716360.218524933;
demand('elec','3') = 253473.224401474;
demand('heat','3') = 610171.446800232;
demand('elec','4') = 238388.124465942;
demand('heat','4') = 675722.227096558;
demand('elec','5') = 263804.799318314;
demand('heat','5') = 662404.716014862;
demand('elec','6') = 211943.902492523;
demand('heat','6') = 540780.808925629;
demand('elec','7') = 297771.082639694;
demand('heat','7') = 628012.437820435;
```

```
demand('elec','8') = 201420.079231262;
demand('heat','8') = 667813.353538513;
demand('elec','9') = 248705.6620121;
demand('heat','9') = 689727.079868317;
demand('elec','10') = 266085.789203644;
demand('heat','10') = 500035.727024078;
demand('elec','11') = 252432.359457016;
demand('heat','11') = 586604.351997375;
demand('elec','12') = 202969.932556152;
demand('heat','12') = 752465.553283691;
demand('elec','13') = 290741.793870926;
demand('heat','13') = 777948.987483978;
demand('elec','14') = 269962.737560272;
demand('heat','14') = 508660.495281219;
demand('elec','15') = 213617.943525314;
demand('heat','15') = 676615.524291992;
demand('elec','16') = 214667.323112488;
demand('heat','16') = 784331.53629303;
demand('elec','17') = 270214.708566666;
demand('heat','17') = 726684.086322784;
demand('elec','18') = 247001.261234283;
demand('heat','18') = 812831.26115799;
demand('elec','19') = 302582.473516464;
demand('heat','19') = 680511.164665222;
demand('elec','20') = 329548.139572144;
demand('heat','20') = 667517.137527466;
demand('elec','21') = 336144.669771194;
demand('heat','21') = 630155.398845673;
demand('elec','22') = 263659.123897552;
demand('heat','22') = 735989.797115326;
demand('elec','23') = 216924.338102341;
demand('heat','23') = 788178.358078003;
demand('elec','24') = 217304.520606995;
demand('heat','24') = 641206.316947937;
demand('elec','25') = 257520.691156387;
demand('heat','25') = 842820.32251358;
demand('elec','26') = 342211.194038391;
demand('heat','26') = 714709.000587463;
demand('elec','27') = 230956.043958664;
demand('heat','27') = 648716.931343079;
demand('elec','28') = 336092.998027802;
demand('heat','28') = 697125.389575958;
demand('elec','29') = 285807.591676712;
demand('heat','29') = 788669.812679291;
demand('elec','30') = 331456.136703491;
demand('heat','30') = 670492.315292358;
demand('elec','31') = 344798.875570297;
demand('heat','31') = 855768.032073975;
demand('elec','32') = 227033.916950226;
demand('heat','32') = 752825.601100922;
```

```
demand('elec','33') = 279522.577524185;
demand('heat','33') = 631582.100391388;
demand('elec','34') = 241096.755027771;
demand('heat','34') = 600612.750053406;
demand('elec','35') = 218838.957548141;
demand('heat','35') = 673175.692558289;
demand('elec','36') = 244225.614070892;
demand('heat','36') = 513012.163639069;
demand('elec','37') = 262524.291276932;
demand('heat','37') = 790742.366313934;
demand('elec','38') = 226335.441589355;
demand('heat','38') = 669177.360534668;
demand('elec','39') = 306169.307470322;
demand('heat','39') = 630867.280960083;
demand('elec','40') = 291948.606967926;
demand('heat','40') = 663706.195354462;
demand('elec','41') = 311327.625513077;
demand('heat','41') = 760413.916110992;
demand('elec','42') = 225718.33896637;
demand('heat','42') = 705215.077400208;
demand('elec','43') = 298914.192914963;
demand('heat','43') = 696035.79044342;
demand('elec','44') = 294202.163219452;
demand('heat','44') = 623038.189411163;
demand('elec','45') = 263853.722810745;
demand('heat','45') = 744313.180446625;
demand('elec','46') = 213885.339736938;
demand('heat','46') = 507051.706314087;
demand('elec','47') = 236979.13146019;
demand('heat','47') = 647514.839172363;
demand('elec','48') = 247454.300403595;
demand('heat','48') = 705623.013973236;
demand('elec','49') = 256179.975748062;
demand('heat','49') = 529984.714984894;


*demand(r,i) = demand(r,i)/1000 ;

DISPLAY
  Dist, CF, techcap ;

VARIABLES
  QR (r, i, i1)        flow of r from i to i1
  PR (r, i)     production of r in cell i
  PT (t, i)     production rate of t in i
  AC (r, i)     accumulation of r in i
  CAP           the capital cost
  ENV           environmental impact
  Z             the objective function ;
```

```
POSITIVE VARIABLES
  QR, PT, AC, CAP;

BINARY VARIABLES
  XQ (r, i, i1) if network exists for i between i and i1 ;

INTEGER VARIABLES
  NT (t, i) number of t at i ;

NT.UP('heat_ex',i) = 1000000 ;
NT.UP('ng_boiler',i) = 1000000 ;
NT.UP('biomass_boiler',i) = 1000000 ;

XQ.FX(r,i,i) = 0 ;

EQUATIONS
  ResBal      resource balance
  AcCon             AC must be zero unless a waste or environmental impact
  ProdRate     production rate of resource r in i
  TechRate     technology rate cap
  FlowRate     resource flow between i and i1
  CapDef      definition of capital cost
  EnvDef      definition of capital cost
  ObjDef      definition of objective function ;

* Resource balance for each cell
ResBal(r,i)..         SUM( i1, QR(r,i1,i) ) + PR(r,i)
                        - demand(r,i)/3600 - SUM( i1, QR(r,i,i1) ) =E= AC(r,i) ;

AcCon(nr,i)..          AC(nr,i) =L= 0 ;

* production of resource r in cell i
ProdRate(r,i)..             PR(r,i) =E= SUM( t, CF(t,r)*PT(t,i) ) ;

* production rate of technology t in cell i
TechRate(t,i)..             PT(t,i) =L= NT(t,i)*TechCap(t) ;

* flow of resources between cells
FlowRate(r,i,i1)..     QR(r,i,i1) =L= XQ(r,i,i1)*MaxTrans(r) ;

* capital cost
CapDef..              CAP =E= SUM( (t,i), TechCC(t)*NT(t,i) ) +
                        SUM( (r,i,i1), TransCC(r)*XQ(r,i,i1)*dist(i,i1) +
0.00001*QR(r,i,i1));

* environmental impact
EnvDef..              ENV =E= SUM( (r,i), Rcost(r)*AC(r,i) ) ;

* objective function
```

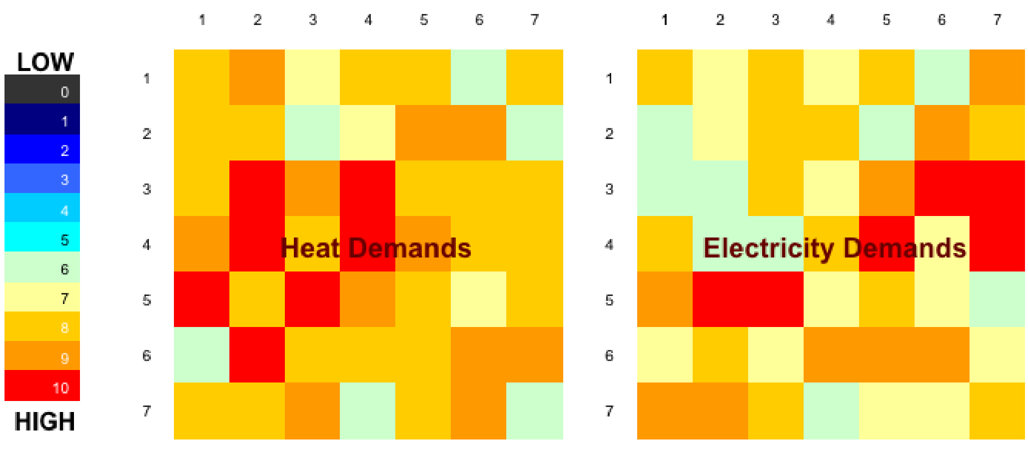
```
ObjDef..        Z =E= CAP/1000 + ENV ;


OPTION ITERLIM = 200000 ;
*OPTION OPTCR = 0.01 ;
MODEL Zeus / ALL / ;
SOLVE Zeus USING MIP MINIMIZING Z ;

DISPLAY Demand, NT.L, PT.L, PR.L, AC.L ;
DISPLAY XQ.L, QR.L ;
DISPLAY CAP.L, ENV.L, Z.L ;
```

Table 7: Heat and electricity demands per cell number

Type of Demand (cell number)	Value
demand('elec','01')	269206.4
demand('elec','02')	247891.8
demand('elec','03')	253473.2
demand('elec','04')	238388.1
demand('elec','05')	263804.8
demand('elec','06')	211943.9
demand('elec','07')	297771.1
demand('elec','08')	201420.1
demand('elec','09')	248705.7
demand('elec','10')	266085.8
demand('elec','11')	252432.4
demand('elec','12')	202969.9
demand('elec','13')	290741.8
demand('elec','14')	269962.7
demand('elec','15')	213617.9
demand('elec','16')	214667.3
demand('elec','17')	270214.7
demand('elec','18')	247001.3
demand('elec','19')	302582.5
demand('elec','20')	329548.1
demand('elec','21')	336144.7
demand('elec','22')	263659.1
demand('elec','23')	216924.3
demand('elec','24')	217304.5
demand('elec','25')	257520.7
demand('elec','26')	342211.2
demand('elec','27')	230956
demand('elec','28')	336093
demand('elec','29')	285807.6
demand('elec','30')	331456.1

demand('elec','31')	344798.9
demand('elec','32')	227033.9
demand('elec','33')	279522.6
demand('elec','34')	241096.8
demand('elec','35')	218839
demand('elec','36')	244225.6
demand('elec','37')	262524.3
demand('elec','38')	226335.4
demand('elec','39')	306169.3
demand('elec','40')	291948.6
demand('elec','41')	311327.6
demand('elec','42')	225718.3
demand('elec','43')	298914.2
demand('elec','44')	294202.2
demand('elec','45')	263853.7
demand('elec','46')	213885.3
demand('elec','47')	236979.1
demand('elec','48')	247454.3
demand('elec','49')	256180
demand('heat','01')	685352.6
demand('heat','02')	716360.2
demand('heat','03')	610171.4
demand('heat','04')	675722.2
demand('heat','05')	662404.7
demand('heat','06')	540780.8
demand('heat','07')	628012.4
demand('heat','08')	667813.4
demand('heat','09')	689727.1
demand('heat','10')	500035.7
demand('heat','11')	586604.4
demand('heat','12')	752465.6
demand('heat','13')	777949
demand('heat','14')	508660.5
demand('heat','15')	676615.5
demand('heat','16')	784331.5
demand('heat','17')	726684.1
demand('heat','18')	812831.3
demand('heat','19')	680511.2
demand('heat','20')	667517.1
demand('heat','21')	630155.4
demand('heat','22')	735989.8
demand('heat','23')	788178.4
demand('heat','24')	641206.3
demand('heat','25')	842820.3
demand('heat','26')	714709
demand('heat','27')	648716.9

demand('heat','28')	697125.4
demand('heat','29')	788669.8
demand('heat','30')	670492.3
demand('heat','31')	855768
demand('heat','32')	752825.6
demand('heat','33')	631582.1
demand('heat','34')	600612.8
demand('heat','35')	673175.7
demand('heat','36')	513012.2
demand('heat','37')	790742.4
demand('heat','38')	669177.4
demand('heat','39')	630867.3
demand('heat','40')	663706.2
demand('heat','41')	760413.9
demand('heat','42')	705215.1
demand('heat','43')	696035.8
demand('heat','44')	623038.2
demand('heat','45')	744313.2
demand('heat','46')	507051.7
demand('heat','47')	647514.8
demand('heat','48')	705623
demand('heat','49')	529984.7



8.2 Appendix B – Calorific values per fuel

Table 8: Calorific Values used for the scenario building (DEFRA, 2011)

Fuel	Calorific Value (GJ/tonne)
Natural gas	52.82
Coal	25.4
Biomass (wood chips)	14.74
Municipal solid waste	9.50

8.3 Appendix C – Input data for Eco-town

Annual Material and Energy Flows with GHG Emission Factors (EF)for Various Sectors in the City of Marston Vale, UK (MFA)

Scenario	sector/use	community-wide annual urban material/energy flows (MFA) (GWh/year)	data source for MFA	tonnes of material (tonnes/year)	Assumptions	GHG emission factor (EF) (kgCO2e/kWh)	EF data source	total GHG emitted = MFA x EF (tCO2eq)	total GHG emitted per capita (tCO2eq/person)
A. "Base Case" NG & Grid	Electricity	75	Entec Report	1.11E+07	Assuming ratio of 1 NG: 0.75 Coal based on Berr UK elec Grid Mix of (43.5% NG, 33% Coal, 16.1% Nuclear, etc) Coal Gross CV = 25.4 GJ/tonne	0.542	DEFRA	40650	6.25
	Heat	188	Entec Report	3.57E+07	Using Natural Gas with CV = 52.82 GJ/tonne	0.185	DEFRA	34780	5.35
							Total for A	75430	11.60
B. Natural Gas	Electricity & Heat	263	Entec Report	5.00E+07	Using Natural Gas with CV = 52.82 GJ/tonne	0.185	DEFRA	48655	7.49
							Total for B	48655	7.49
C. Biomass (Grid + Biomass CHP)	Electricity	50	Assume 33% comes from Biomass CHP	7.40E+06	Assuming ratio of 1 NG: 0.75 Coal based on Berr UK elec Grid Mix of (43.5% NG, 33% Coal, 16.1% Nuclear, etc) Coal Gross CV = 25.4 GJ/tonne	0.542	DEFRA	27100	4.17
	Heat	188	Entec Report	3.57E+07	Using Natural Gas with CV = 52.82 GJ/tonne	0.185	DEFRA	34780	5.35
	Tonnes of Biomass per year	25	Entec Report	1.33E+06	Using Wood Chips with CV = 14.74 GJ/tonne	0.0158	DEFRA	394.75	0.06
							Total for C	62275	9.58
D. Waste to Energy (Anaerobic Digestion)	Municipal Solid Waste	52.6	Assume 20% of total energy demand	1.80E+06	Using MSW with Gross CV = 9.5 GJ/tonne (DTI)	-0.252	DEFRA (-664 kgCO2e/tonne waste treated by AD)	-13255.2	-2.04
	Electricity	60	Entec Report	8.87E+06	Assuming ratio of 1 NG: 0.75 Coal based on Berr UK elec Grid Mix of (43.5% NG, 33% Coal, 16.1% Nuclear, etc) Coal Gross CV = 25.4 GJ/tonne	0.542	DEFRA	32520	5.00
	Heat	150.4	Entec Report	2.86E+07	Using Natural Gas with CV = 52.82 GJ/tonne	0.185	DEFRA	27824	4.28
							Total for D	47088.8	7.24
E. Mixed Renewables	Electricity from Renewables (eg. PV cells + Wind Turbines)	14.6	Celine's Paper (Consumption Profiles)	2.16E+06	Assume solar electricity from PV (0.04 kgCO2e/kWh) and wind by horizontal axis turbine (0.01 kgCO2e/kWh) (Take average)	0.025	GE and www.sourcemap.org/power	365	0.06
	Heat from Renewables (eg. Heat Pump + Solar Thermal Collectors)	8.43	Celine's Paper (Consumption Profiles)	1.60E+06	Assume solar thermal from solar collectors (0.01 kgCO2e/kWh) and heat pump with COP4 (0.13 kgCO2e/kWh) (Take average)	0.07	heatpumps.co.uk and www.sourcemap.org/power	590.1	0.09
	Electricity from Grid	66.6	Entec Report	9.85E+06		0.542	DEFRA	36097	5.55
	Heat from Natural Gas	173.4	Entec Report	3.30E+07		0.185	DEFRA	32079	4.94
							Total for D	69131	10.64

Annual Material and Energy Flows with GHG Emission Factors (EF)for Various Sectors in the City of Toronto, Canada (MFA)

Scenario	sector/use	community-wide annual urban material/energy flows (MFA) (GWh/year)	data source for MFA	tonnes of material (tonnes/year)	Assumptions	GHG emission factor (EF) (kgCO2e/kWh)	EF data source	total GHG emitted = MFA x EF (tCO2eq)	total GHG emitted per capita (tCO2eq/person)
A. "Base Case" NG & Grid	Electricity	29878	Toronto's Sustainable Energy Plan	3.57E+09	Assuming ratio of 1 NG: 2.5 Coal based on Canada elec Grid Mix of (58.7% hydroelectricity, 6.6% NG, 16.6% Coal, 15.5% Nuclear, etc) Coal Gross CV = 25.4 GJ/tonne	0.542	DEFRA	16193876	6.23
	Heat	42657	Toronto's Sustainable Energy Plan	8.11E+09	Using Natural Gas with CV = 52.82 GJ/tonne	0.185	DEFRA	7891545	3.04
							Total for A	24085421	9.26
B. Natural Gas	Electricity & Heat	72535	Toronto's Sustainable Energy Plan	1.38E+10	Using Natural Gas with CV = 52.82 GJ/tonne	0.185	DEFRA	13418975	5.16
							Total for B	13418975	5.16
C. Biomass (Grid + Biomass CHP)	Electricity	19919	Assume 33% comes from Biomass CHP	2.38E+09	Assuming ratio of 1 NG: 2.5 Coal based on Canada elec Grid Mix of (58.7% hydroelectricity, 6.6% NG, 16.6% Coal, 15.5% Nuclear, etc) Coal Gross CV = 25.4 GJ/tonne	0.542	DEFRA	10796098	4.15
	Heat	42657	Toronto's Sustainable Energy Plan	8.11E+09	Using Natural Gas with CV = 52.82 GJ/tonne	0.185	DEFRA	7891545	3.04
	Tonnes of Biomass per year	9959	Toronto's Sustainable Energy Plan	5.28E+08	Using Wood Chips with CV = 14.74 GJ/tonne	0.0158	DEFRA	157252.61	0.06
							Total for C	18844896	7.25
D. Waste to Energy (Anaerobic Digestion)	Municipal Solid Waste	14507	Assume 20% of total energy demand	4.96E+08	Using MSW with Gross CV = 9.5 GJ/tonne (DTI)	-0.252	DEFRA (-664 kgCO2e/tonne waste treated by AD)	-3655764	-1.41
	Electricity	23902	Toronto's Sustainable Energy Plan	2.86E+09	Assuming ratio of 1 NG: 2.5 Coal based on Canada elec Grid Mix of (58.7% hydroelectricity, 6.6% NG, 16.6% Coal, 15.5% Nuclear, etc) Coal Gross CV = 25.4 GJ/tonne	0.542	DEFRA	12954884	4.98
	Heat	34126	Toronto's Sustainable Energy Plan	6.49E+09	Using Natural Gas with CV = 52.82 GJ/tonne	0.185	DEFRA	6313310	2.43
							Total for D	15612430	6.00
E. Mixed Renewables	Electricity from Renewables (eg. PV cells + Wind Turbines)	150.0	Assume 0.5% of total electriciy	1.80E+07	Assume solar electricity from PV (0.04 kgCO2e/kWh) and wind by horizontal axis turbine (0.01 kgCO2e/kWh) (Take average)	0.025	GE and www.sourcemap.org/power	3750	0.00
	Heat from Renewables (eg. Heat Pump + Solar Thermal Collectors)	213.00	Assume 0.5% of total heat	4.05E+07	Assume solar thermal from solar collectors (0.01 kgCO2e/kWh) and heat pump with COP4 (0.13 kgCO2e/kWh) (Take average)	0.07	heatpumps.co.uk and www.sourcemap.org/power	14910	0.01
	Electricity from Grid	29728	Toronto's Sustainable Energy Plan	3.56E+09		0.542	DEFRA	16112576	6.20
	Heat from Natural Gas	42444	Toronto's Sustainable Energy Plan	8.07E+09		0.185	DEFRA	7852140	3.02
							Total for E	23983376	9.22

Ecological Footprints for different energy systems in Marston Vale

Scenario	Energy Source	Consumption (GWh)	data source for MFA	Ecological Footprint* (ha)	EF data source	Ecological Footprint per capita (ha/person)
A. "Base Case" NG & Grid	Electricity	75	Entec Report	11250	York Paper, assuming EF for producing 1 GWh of electricity = 150 ha/GWh	1.73
	Heat	188	Entec Report	12220	York Paper, assuming EF for producing 1 GWh of gas = 65 ha/GWh	1.88
			Total EF for A	**23470**	**Total for A**	**3.61**
B. Natural Gas	Electricity & Heat	263	Entec Report	17095	DEFRA	2.63
			Total EF for A	**16656**	**Total for B**	**2.56**
C. Biomass (Grid + Biomass CHP)	Electricity	50	Assume 33% comes from Biomass CHP	7500	DEFRA	1.15
	Heat	188	Entec Report	12220	DEFRA	1.88
	Tonnes of Biomass per year	25	Entec Report	407	DEFRA	0.06
		Assume CV of woodchips = 14.74 GJ/tonne	Assume 15 tonne biomass/ha	**20127**	**Total for C**	**3.10**
D. Waste to Energy (Anaerobic Digestion)	Municipal Solid Waste	52.6	Assume 20% of total energy demand	50	Assume 400 tonne MSW/ha (http://www.environment-agency.gov.uk/static/documents/Business/Financial_impact_assessment_for_anaerobic_digestate.pdf)	0.01
	Electricity	60	Entec Report	9000	York Paper	1.38
	Heat	150.4	Entec Report	9776	York Paper	1.50
			Total EF for D	**18826**	**Total for D**	**2.90**
E. Mixed Renewables	Electricity from Renewables (eg. PV cells + Wind Turbines)	14.60	Weber C., (2011) Paper (Consumption Profiles)	219	York Paper, assuming EF for producing 1 GWh from PV = 24 ha/GWh and from wind = 6 ha/GWh (Take average)	0.03
	Heat from Renewables (eg. Heat Pump + Solar Thermal Collectors)	8.4	Weber C., (2011) Paper (Consumption Profiles)	0	Assume 0 emission factor	0.00
	Electricity from Grid	66.6	Entec Report	9990	York Paper	1.54
	Heat from Natural Gas	173.4	Entec Report	11271	York Paper	1.73
			Total EF for E	**21480**	**Total for E**	**3.30**

Ecological Footprints for different energy systems in Toronto

Scenario	Energy Source	Consumption (GWh)	data source for MFA	Ecological Footprint* (ha)	EF data source	Ecological Footprint per capita (ha/person)
A. "Base Case" NG & Grid	Electricity	29878	Toronto's Sustainable Energy Plan	4481700	York Paper, assuming EF for producing 1 GWh of electricity = 150 ha/GWh	1.72
	Heat	42657	Toronto's Sustainable Energy Plan	2772705	York Paper, assuming EF for producing 1 GWh of gas = 65 ha/GWh	1.07
			Total EF for A	**7254405**	**Total for A**	2.79
B. Natural Gas	Electricity & Heat	72535	Toronto's Sustainable Energy Plan	4714775	DEFRA	1.81
			Total EF for A	**4714775**	**Total for B**	1.81
C. Biomass (Grid + Biomass CHP)	Electricity	19919	Assume 33% comes from Biomass CHP	2987850	DEFRA	1.15
	Heat	42657	Toronto's Sustainable Energy Plan	2772705	DEFRA	1.07
	Tonnes of Biomass per year	9959	Toronto's Sustainable Energy Plan	162153	DEFRA	0.06
		Assume CV of woodchips = 14.74 GJ/tonne	Assume 15 tonne biomass/ha	**5922708**	**Total for C**	2.28
D. Waste to Energy (Anaerobic Digestion)	Municipal Solid Waste	14507	Assume 20% of total energy demand	13743	Assume 400 tonne MSW/ha (http://www.environment-agency.gov.uk/static/documents/Business/Financial_impact_assessment_for_anaerobic_digestate.pdf)	0.01
	Electricity	23902	Toronto's Sustainable Energy Plan	3585300	York Paper	1.38
	Heat	34126	Toronto's Sustainable Energy Plan	2218190	York Paper	0.85
			Total EF for D	**5817233**	**Total for D**	2.24
E. Mixed Renewables	Electricity from Renewables (eg. PV cells + Wind Turbines)	150.0	Assume 0.5% of total electriciy	2250	York Paper, assuming EF for producing 1 GWh from PV = 24 ha/GWh and from wind = 6 ha/GWh (Take average)	0.00
	Heat from Renewables (eg. Heat Pump + Solar Thermal Collectors)	213.00	Assume 0.5% of total heat	0	Assume 0 emission factor	0.00
	Electricity from Grid	29728	Toronto's Sustainable Energy Plan	4459200	York Paper	1.72
	Heat from Natural Gas	42444	Toronto's Sustainable Energy Plan	2758860	York Paper	1.06
			Total EF for E	**7220310**	**Total for E**	2.78