Using Municipal Solid Waste Composition Data to Estimate the Carbon Footprint of Managing UK MSW: A Method to Assist Waste Management Firms with Strategic Planning and Compliance with Emerging EU Legislation

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Preface

As an avid Blue Peter fan growing up in the 1990's, I was familiar with terms such as "global warming", "the greenhouse effect", and "the hole in the ozone layer". By the time I started University in 2000, one of these terms had been relegated to reference in the past-tense only, largely due to the successful implementation of the Montreal Protocol that banned the use of the substances (CFCs) responsible for creating the hole in the ozone layer. The other terms remain firmly in the present, indeed, by the time I'd completed my undergraduate degree the Kyoto Protocol was floundering as climate change sceptics fortified their positions in the US and Australia. As I complete my Doctoral studies, thankfully, times have changed – a changing of the guard in both countries has given global warming and climate change the focus I feel it has needed for over decade.

Sure, I'm not a climatologist and I would never claim to understand or comprehend a system as complex and dynamic as Gaia. But applying the same logic of Pascal's Wager to the issue of anthropogenic climate change has had me convinced that reducing greenhouse gas emissions can only be a good thing. On the subject of the existence of God, Blaise Pascal wagered that it was better to believe in God and Him not to exist, rather than not believing and consequently finding yourself in Hades because God actually does exist, in Pascal's words: *If you gain, you gain all; if you lose, you lose nothing*. Applied to anthropogenic climate change, the wager is that it is better to believe in the consequences of climate change and to mitigate greenhouse gas emissions even if the change is due to natural factors, rather than doing nothing and realising that the resulting catastrophic climate shift was indeed due to anthropogenic activity. The gains are huge: a habitable planet and the continuing existence of our species. If the sceptics are right and it turns out to be natural cycle, then the "losses" are not too bad either: clean energy supplies, sustainable living, revolutionary transport systems, etc.

The UN secretary general, Ban Ki Moon, describes climate change and global warming as "*the defining challenge of our age*". This thesis is my first contribution to this challenge.

Acknowledgements

I am indebted to my supervisor, Professor David Stupples, for his belief in the research and whose encouragement, support, and guidance throughout have made this thesis possible (not to mention structured and lucid). But most importantly, for introducing me to systems thinking and engineering, which has radically changed my approach to problem solving; forever.

Like most projects, this one would not have been possible without funding. I owe my deepest gratitude to David Savory of Biffa Waste Services, not just for writing cheques but also for his endless commitment and belief in me and the research. I extend this gratitude to Gill Treanor for her constant guidance and support; to Graham Wilkins for his assistance with sense checking model outputs; to Lynn Clarke, Gillian Sinclair and Hannah Forbes for providing verification data; and also to the IT department for getting WRATE to work. I am grateful also for the financial support of Atco Power and would specifically like to thank Gawain Paling, Mike Lees, and Richard Hodgson for their constructive input during hours of progress reports.

I would also like to extend my thanks to members of City's academic staff. To Dr Godoy who cultivated my interest in sustainability and renewable energy during my undergraduate studies. To Dr Lockett, without whose lectures on Schrödinger and his famed cat, and all other things quantum, would have made comprehending the physics of global warming a formidable task. I am grateful to Professor Newby for his patience (and persistence) in explaining the subtle aspects of probability theory. And to Professor Thomas, whose guidance in how to assemble words into paragraphs and pages into chapters was incredibly simple and yet so effective.

In completing this thesis I have come to realise that for certain subjects there is no substitute for expert elicitation. In particular, I offer my thanks to John Barton of the University of Leeds for his helpful discussions about the finer points of waste legislation and life-cycle assessment; and to Dr Duncan Boorman, also of the University of Leeds, for helping me grasp the concepts of numerical simulation.

Thanks also to all of my contemporaries in the post-graduate office at City for keeping me fit (and sane) on the five-a-side pitch; and in particular to Messrs Free and Pearce for regular, jovial discussions over coffee. To the numerous friends and family who have given their endless support and encouragement throughout all of my studies, I can at last offer a satisfactory response to your perpetual question. Yes, I've finished writing the thesis.

And finally, to Katie, my muse, for her never-ending understanding and support throughout, to whom I dedicate this thesis.

Declaration

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Abstract

Greenhouse gases released into the atmosphere from anthropogenic activity absorb infrared radiation. As atmospheric concentrations increase, so too does the temperature at the Earth's surface. Consequently, environmental legislation targeted at specific gases and sectors has been introduced across the EU. Expressing greenhouse gas emissions as carbon dioxide equivalents enables their impact to be directly compared and provides a measure of compliance. As a result, emissions released by an activity are commonly referred to as its carbon footprint.

A systems approach has been applied to managing MSW in the UK with a specific focus on mitigating greenhouse gas emissions. The life-cycle assessment tool, WRATE, identified that the carbon footprint is dominated by waste treatment processes and transportation, rather than typical sources such as energy consumption and resource use. Process emissions are directly related to waste composition and are released as waste is chemically or biologically transformed. Waste composition is paramount to the carbon footprint yet it is poorly reported in the UK.

A modelling approach is presented using waste composition to estimate the carbon footprint from managing waste. A hypothetical compound of the form $C_aH_bO_cN_d$ is used to approximate waste composition and to model the biological and chemical transformation of waste. A novel application of Monte Carlo analysis is employed to examine how parametric uncertainties influence composition and thus provide limits to the size of the carbon footprint.

The method is applied to a UK waste management contract and indicates that the correct waste management strategy could increase renewable energy generation from bio-gas and thermal treatment processes, thus displacing fossil fuel derived emissions. Alternatively, comprehensive recycling could lead to a lower overall carbon footprint because of the emissions displaced by substituting virgin materials with recyclables. Where the emissions boundary is drawn and, within the boundary, how emissions are counted is critical to the success of a carbon reduction strategy

Prologue

Introduction

Climate change is a global phenomenon and the contribution from anthropogenic activity is one of the most hotly contested debates of modern times. Those countries who acknowledge that the technological development of humankind is influencing the global mean surface temperature on Earth have, in general, ratified the Kyoto Protocol and are moving towards reducing their emissions of greenhouse gases. The introduction of environmental legislation across the EU, targeted at specific gases and sectors, coupled with emissions trading, has placed the responsibility of carbon management with large businesses and corporations. For those countries that did not ratify the Kyoto Protocol, rising oil prices have led to an increase in investment in alternative technologies and fuels. The result, ratification or not, is that carbon footprints and carbon management have become buzzwords in the boardroom and in the political arena, and the waste management sector is no exception.

Methane emissions from waste management activities were cited in the Kyoto Protocol as a significant source of greenhouse gases and legislation has been implemented to restrict methane generation. This is drawing to a close an era in which landfill dominated UK waste management routes. Other climate change related policy amendments such as technology banding in the Renewable Obligation Order, has resulted in thermal treatment technologies receiving different levels of financial support for the renewable energy they generate; the quantity of renewable energy that qualifies for this support is directly related to the composition of the waste processed. Therefore, waste management companies are faced with a dilemma over which technologies to pursue as an alternative to landfill because each mix of technology options will have different carbon profiles, will be sensitive to different waste parameters, and will contribute to achieving legislative compliance in different ways. In addition, impending changes to the EU waste framework directive that will reclassify some thermal treatment technologies as recovery options and that will also encourage separate biowaste collection have further added to the complexity of managing UK waste.

Existing appraisal methods are rooted in subjective decision making using the waste management hierarchy or a 'black box' approach such as that used in the Environment Agency's life-cycle assessment (LCA) tool, WRATE. Difficulties arise with using these types of methods to make strategic planning decisions. For example, the waste management hierarchy intuitively ranks technologies in order of preference but says nothing about the sensitivity of each technology's environmental performance to waste composition. WRATE allows a more objective assessment of waste technologies by employing a LCA approach that considers the effect of waste composition on environmental impacts. However, these impacts are scaled relative to observed technology inputs and outputs rather than based on the technology process itself. And being a LCA tool, all burdens and benefits are reported on a levelised basis which collapses the methane emissions and expresses the total emitted in that year, rather than considering the evolution of the emissions profile – understanding the emissions profile enables a more realistic assessment of a firm's carbon liability, or perhaps more importantly, their carbon legacy.

Therefore, what is needed is a scientifically based approach that can estimate the carbon footprint from managing UK MSW, which is linked to the underlying technology processes, i.e. to how the chemical composition of waste influences the carbon profile and legislative compliance of technologies. This type of approach will enable the sensitivity of technologies to waste composition to be compared and assessed objectively and thus assist waste management companies with strategic planning in order to meet emerging EU legislation and reduce their carbon equivalent emissions profile.

This may seem like a tall order, but if greenhouse gas emissions are to be significantly reduced then corporations and firms alike can only (and should only) actively participate if they can understand the true impact of carbon on their business. This is pertinent to waste management since thermal treatment technologies can generate renewable electricity and earn additional revenue streams from mechanisms such as renewable obligation certificates. The electricity that qualifies for the certificates is determined from the energy content of the biowaste fraction relative to the total energy content of the waste treated. However, the typically high moisture content of biowaste significantly reduces its calorific value and, therefore, its renewable electricity generating potential. There is clearly a need to balance income from electricity sales with revenue from renewable obligation certificates whilst maintaining regulatory compliance and without detrimental impact to the carbon footprint. The approach presented in this thesis specifically addresses this problem.

Objectives

The objective of this thesis is to:

Develop a scientifically based estimation of the carbon dioxide equivalent emissions arising from managing UK MSW, based on its chemical composition, in order to assist waste management companies (WMCs) with strategic planning and compliance with emerging EU legislation.

In order to achieve this objective, the following secondary objectives are addressed:

- SO-1. Identify the legislative constraints pertinent to managing waste
- SO-2. Identify how the management of waste contributes to climate change and global warming
- SO-3. Show that waste management can be modelled as a system
- SO-4. Develop a model that estimates the evolution of the carbon footprint
- SO-5. Identify the waste management processes that dominate the carbon footprint

SO-6. Gather suitable data to facilitate the testing and verification of the carbon footprint model

SO-7. indicate what measures are necessary to reduce the carbon footprint and provide indicative costs that can be used to inform strategic decisions

Achieving the Objectives

The secondary objectives are addressed in various chapters of the thesis, as reported in Table 1. The principal and secondary objectives are revisited and discussed explicitly in Chapter 7.

Objectives	2	3	4	5	6
SO-1	•				
SO-2		•		•	•
SO-3			•		
SO-4				•	•
SO-5				•	•
SO-6					•
SO-7					•

Table 1: Location in the thesis identifying where the Secondary Objectives are addressed

Summary of Findings

Systems analysis methods have been used to identify the dominant carbon sources and sinks from managing waste in order to develop a model that estimates the carbon dioxide equivalent emissions arising from managing UK municipal solid waste. The findings from this research indicate that:

- Waste policy is interlinked with other climate change themed legislation and that regulatory compliance has the potential to jeopardise the spirit of Kyoto. Equally, the correct choice of technologies could achieve compliance and mitigate greenhouse gas emissions not only within the waste sector but also across other industries.
- Methane's role in global warming, particularly its removal from the atmosphere is complex and influenced by combustion products. Reporting a carbon footprint at various different emissions boundaries offers immense value when identifying strategic waste management options.
- Different modelling techniques have been successfully applied to waste management problems at a variety of spatial scales, but showed that little analysis had been undertaken at the level of the firm.
- By approximating waste composition as a hypothetical compound of the form $C_aH_bO_cN_d$, Monte Carlo simulations can be used to examine how parametric uncertainties influence composition. The results indicated that $C_6H_{10}O_3$ was a reasonable approximation of UK MSW and that on a dry basis this structure remains fairly constant, which indicates that it is the properties of each individual waste fraction that influence the chemical transformation of waste into other products.
- The chemical composition of MSW on the Black Peninsula, a fictionalised English county, is fairly consistent in chemical composition from 1998 to 2007, indicating that the processes used to treat waste will determine the quantity of greenhouse gas emissions released from the waste. For example, biodegradation will release less CO_2 than combustion because much of the carbon in the waste remains stored in stabilised material. Whereas if combusted, all of the carbon is released as CO_2.

- The conceptual location of emissions boundaries, in particular, whether domestic or non-UK has significant impact on the magnitude of the carbon footprint. Inclusion of biogenic carbon emissions in the carbon footprint suggest that energy recovery from waste will have little impact on reducing UK carbon emissions. However, recovering energy from waste will preserve abiotic resources and offer a secure energy source whilst complying with European renewable energy targets.

Thesis Structure

The thesis is arranged into the following chapters: Prologue, Solid Waste in Society, Footprints in the Sky, Understanding Systems, Model Development, Application of the Research Model to PenWaste, Summary and Conclusions, Appendices, and References. The first chapter sets the scene and states the objectives and findings of the research. Chapter 2, Solid Waste in Society, discusses the types of waste that arise in the UK and documents the current and future legislation applicable to the waste industry, before presenting a brief overview of the technologies that exist to manage waste. Chapter 3, Footprints in the Sky, provides a backdrop to climate change; the notion of carbon footprints is introduced and waste management's role in climate change is discussed, highlighting the complexity of the problem. With the scene set, Chapter 4, Understanding Systems, presents and discusses the systems approach to solving problems; waste management is then defined as a system and models and techniques that have been applied to waste management are reviewed.

The defining chapters of the thesis present and test the Research Model. In Chapter 5, the Research Model is developed using functional analysis. Techniques for modelling each of the sub-functions are presented and discussed before outlining how each is integrated to form a system dynamics model capable of meeting the principal objective of the work. Chapter 6 presents a case study of the waste management contract on the Black Peninsula operated by PenWaste, a fictionalised waste management company. Data collected for the case study is used to populate the research model to first test its credibility and then to explore how sensitive the carbon footprint is to specific parameters including emissions boundaries and waste composition.

The final chapter, Summary and Conclusions, gathers all of the conclusions from the research, with particular emphasis on how the objectives have been achieved. The thesis is then concluded with recommendations based on the findings of the research and directions for further work. A list of all referenced material follows the Appendices.

Summary and Conclusion

"It is a most mortifying reflection for a man to consider what he has done, compared to what he might have done." **Samuel Johnson**

Overview

This chapter provides a summary of the findings pertinent to each chapter of the thesis and discusses the key findings in more detail. The objectives of the research are revisited and recommendations emerging from the thesis are discussed. Finally, limitations to the approach and areas for future research are presented.

Summary of Findings from the Research

Chapter 2 defined waste as a product that has lost value and is therefore discarded. An overview of the waste streams generated in the UK was presented and the typical types of technology solutions used to manage this waste were summarised. Because traditional management routes were a significant source of methane, MSW has been heavily regulated yet other waste streams seem to have been largely ignored. This chapter showed that waste policy is not exogenous in terms of Kyoto, rather that it is interrelated with other climate change themed legislation, indicating from a regulatory standpoint that at a holistic approach to managing waste is necessary. This chapter also hinted at how recycling and reuse have the potential to make manufacturing processes more closed-loop in the way that raw materials are managed, particularly if the environmental impacts of MSW, commercial, and industrial waste were regulated collectively. The key conclusion from this chapter is that although from a regulatory perspective managing waste is complex, the correct choice of technologies could achieve regulatory compliance while simultaneously mitigating greenhouse gas emissions within the waste sector and in other industries.

Chapter 3 presented definitions of the terms *carbon footprint* and *carbon neutral*, and discussed the importance of choosing the correct emissions boundary and the ease that double counting can occur. The chapter indicated that managing waste has impacts at various emissions boundaries, and depending where these boundaries are drawn can influence the size of a waste management solution's environmental burden. An overview of the theory of global warming was provided and showed that it is a complex phenomenon comprising a number of interacting feedback loops. The chapter also indicated that emissions from waste management activities, particularly fossil fuel combustion, can influence global warming and the removal mechanism of atmospheric methane. The life-cycle of methane was discussed and further highlighted the important role that technology choice has in mitigating greenhouse gas emissions. The key conclusion from this chapter is the importance that emissions boundaries have on the carbon footprint and that being able to include various different levels in the research model will have immense value when identifying strategic waste management options.

Chapter 4 defined some key systems terms used in the thesis and discussed how models can be considered systems in their own right. Despite models being a necessarily incomplete approximation of the system under investigation, this chapter argued that their success can be measured on how useful they are and presented a set of tests that can be undertaken to improve confidence in the model. These key aspects were summarised to form the modelling philosophy used to develop the research model. Examples of systems models applied to waste management problems were presented, which identified that little modelling has been undertaken at the level of the firm. The key conclusion from this chapter is that thorough validation of a model is strictly impossible because the model itself has to be an incomplete representation of the system. However, a model's credibility can be strengthened by virtue of a structured approach to testing.

Chapter 5 outlined the function of the research model and presented methods of estimating emissions from the waste management processes that dominate the carbon footprint. Despite a lack of data related to the physical and chemical composition of UK waste, data from other countries were used to populate a Monte Carlo simulation and estimate waste composition based on parametric uncertainty. A novel approach employed was to approximate the waste composition as a hypothetical compound of the form $C_aH_bO_cN_d$ and examine how the parametric uncertainties influenced its structure. The results of this analysis indicated that $C_6H_{10}O_3$ was a reasonable approximation of UK MSW and furthermore, that this structure was consistent with MSW from other nations. The key conclusion from this chapter is that on a dry basis, the chemical composition of UK waste appears to be fairly constant, despite being heterogeneous in a physical sense. Moreover, this implies that the properties of each individual waste fraction will influence the chemical transformation of the waste into other products – the key example is degradable carbon, for this is essentially the physical limit to which carbon dioxide and methane can be produced in biological processes.

Chapter 6 applied the methods and framework developed in Chapter 5 to PenWaste, the company that manages MSW on the Black Peninsula. Data provided by PenWaste was used to test the credibility of the research model and showed that the model achieves its principal objective: to estimate the carbon footprint from managing waste. Results indicated that a targeted recycling policy coupled with investment in EfW and AD offers a compromise between electricity generation, recycling performance, and mitigating carbon emissions from managing waste. At a local level, the operational life of the Quarry Fills landfill site can be extended, whilst at a national level the proposed strategy contributes to renewable energy targets. The key conclusion from this chapter is that the conceptual location of emissions boundaries, in particular, whether domestic or non-UK has significant impact on the magnitude of the carbon footprint. If biogenic carbon emissions are included in the carbon footprint, then results from the modelling suggest that energy recovery from waste will have little impact on reducing UK carbon emissions. However, recovering energy from waste will preserve abiotic resources and offer a secure energy source whilst complying with European renewable energy targets.

Discussion of Key Findings

The key findings are related to the relative consistency in chemical composition of MSW and sensitivities to the carbon footprint; principally biogenic carbon and emissions boundaries.

Waste Composition

Chemical composition of UK waste on a dry basis was shown to be constant and that the hypothetical compound $C_6H_{10}O_3$ was a good approximation to household and CA waste streams, this chemical composition was also consistent with waste streams from across world. The largest uncertainty associated with the composition of household waste was from the plastics and combustibles fractions. In particular, the chemical composition of each indicated that the range of uncertainty could be reduced by using more specific data. For a waste management firm this has useful implications in that waste analysis should be focused on these two particular fractions to determine what types of plastics are being discarded and what materials are being classed as combustibles. The latter would be of particular use in reducing the uncertainty of chemical composition in CA waste. This is of particular importance if energy is to be recovered from the combustible fraction because all of the available carbon contained in the waste stream will be released during the combustion process. Hence narrowing the band of uncertainty with carbon composition will mean that the uncertainty in size of the carbon footprint will also be reduced. Furthermore, as the renewable energy content can be determined from carbon composition then any reduction in uncertainty intervals will improve the accuracy in estimating renewable energy. Consequently this will improve the projected estimates of revenues from green energy certificates.

The chemical composition of MSW on the Black Peninsula was shown to be fairly consistent from 1998 to 2007 and close to the generalised structure presented in Chapter 5; the typical structure was $C_6H_{9.3}O_{3.3}$. The values for oxygen and hydrogen content lie within the 95% confidence interval for CA waste and the oxygen content is slightly above the 95% upper limit for household waste. This difference arises because the proportions of paper and food waste in MSW managed by PenWaste have increased as school waste collections have become part of the waste management contract. Hence this increase in oxygen content should be expected, given that cellulose has the formula $C_6H_{10}O_5$ and food can be approximated as $C_6H_{10}O_4$. The litter and commercial streams also contain large proportions of green waste that would contribute to an increase in the oxygen content in the MSW.

However, commercial and school wastes were not reported in the waste surveys reviewed in Chapter 5. Hence if Black Peninsula is a typical example of UK MSW, then perhaps MSW should be approximated as $C_6H_9O_3$ and domestic waste be approximated as $C_6H_{10}O_3$. Because of the influence of tourism on Black Peninsula it could be likely that its MSW composition is atypical, particularly as examples of MSW from other countries were found to be consistent with the structure $C_6H_{10}O_3$.

Key Conclusion

The proportions of carbon, hydrogen and oxygen that constitute MSW are reasonably constant, even with high recycling rates. Since it is these elements that will decompose or combust and release greenhouse gases, then per tonne of non-inert MSW, there is only a finite quantity of carbon that can be released into the atmosphere. Hence the processes used to treat waste will determine the quantity of greenhouse gases emitted. For example, biodegradation will release less CO_2 than combustion because much of the carbon in the waste remains stored in stabilised material. Whereas if combusted, almost all of the carbon is released as CO_2.

Defining the Carbon Footprint

The critical element to defining a waste management firm's carbon footprint is first defining the meaning of *carbon neutral.* Burtis and Watt (2008) proposed the definition as "*no net increase of atmospheric greenhouse gases from the existence of the firm or the products it produces*". Findings from this research support this definition, but as much of the displaced greenhouse gas emissions occur off shore, this will be detrimental to the UK and the firm's carbon footprint. However, the clue is in its title: global warming. By its very magnitude it requires a global solution, i.e. each nation reducing global greenhouse gas emissions. Hence it is inappropriate to have a boundary at any other level than that which encompasses Gaia.

A systems dynamics perspective supports this definition too. As global warming is a result of greenhouse gases in the atmosphere absorbing IR radiation and radiating it back to the Earth's surface, then it is necessary to reduce the greenhouse gases in the atmosphere, which if considered as a stock or level can be achieved in three possible ways. Firstly, reduce emissions of greenhouse gases to rates lower than the absorption rates of carbon sinks, which will eventually cause atmospheric concentrations to reduce (whereas matching emissions rates with absorption rates will stabilise atmospheric concentration). Secondly, Increase absorption rates of carbon sinks so that they exceed the rate of emissions. Thirdly, decrease emissions and increase absorption rates.

Although the above solution is on the surface simple, the complexity of global warming and its relationship with the climate cannot be emphasised enough. But it is the feedback between sources and sinks that is complex and thus why the solution is far more complicated than just increasing absorption and decreasing emissions. Nevertheless, it highlights the need for a global emissions boundary for greenhouse gases, which therefore has to include biogenic carbon dioxide emissions.

Discounting the impact of biogenic carbon reduces the carbon footprint wherever the emissions boundary is drawn and is especially prevalent in energy policy, where biomass fuels are assigned an emissions factor equal to zero. As fuels switch to biomass or biogenic rich sources, such as refuse derived fuel, fossil carbon emissions throughout the UK would be reduced. But it is not just fossil-carbon dioxide that absorbs IR radiation, so the trade-off is a reduction in fossil fuel based CO_2 in favour of a rise in overall CO_2 emissions.

But as the analysis of Chapter 6 showed, diverting biogenic recyclables to recover energy not only increases total emissions relative to energy generation from fossil fuels, but also reduces the emissions that would have been displaced by recycling the fractions instead. Waste combustion is therefore useful to conserve abiotic resources, but not to displace CO_2 emissions. Hence a key environmental benefit is gained from conserving fossil fuel use.

If the focus of waste management policy is actually on preventing CO_2 from being emitted, then biodegradation is critical because of the amount of carbon that can be sequestrated. Moreover, if this degradation occurs under anaerobic conditions then the biogas produced can be used to generate energy, which will of course yield CO_2 in the combustion products, but CO_2 would have been released as a by product of the degradation process anyway.

The plastics in the waste stream cannot be biologically degraded and most cannot be recycled. Findings from this research suggest two possible disposal routes. The first is fuel for a cement kiln (or any other process that uses coal) if the calorific value is higher enough to result in a carbon offset, i.e. the amount of carbon emitted in the combustion process is less than the emissions factor of coal (and even a marginal reduction in CO_2 would still have the benefit of preserving coal reserves). The second route is, ironically, landfill because burying the plastic sequesters the carbon and because plastic contains negligible degradable organic carbon there would be no landfill gas generated – interestingly, this point was raised by a House of Lords Select Committee in 1998 prior to the Landfill Directive entering into force.

Key Conclusion

A waste management firm is well placed to assist reduction in global greenhouse gas emissions, but at the expense of its own green credentials (if this is measured by carbon footprints). Recycling metals, glass and textiles from all MSW fractions is likely to compensate for carbon emissions released during electricity generation, even if mass-burn incineration is used without combined heat and power (CHP). Coupled with anaerobic treatment of kitchen and garden waste, this combined approach will reduce global emissions and allow waste management firms to exploit the financial rewards associated with renewable energy generation. However, a comprehensive recycling strategy could have a huge impact on reducing global emissions but without the financial reward of energy generation and the political benefit of reducing the dependence of fossil fuels.

Revisiting the Objectives

This section formally addresses the primary and secondary objectives of the thesis that were presented in Chapter 1.

Primary Objective

Given the physical laws that govern emissions from waste (i.e. mass balance), understanding the chemical composition of waste is paramount in mitigating the impact of those emissions. The scientific approach adopted in this thesis to estimate such emissions is not new. Approximating waste streams as hypothetical compounds has been widely used in the US, but less so in the UK. The comprehensive application of the approach to waste management processes in the UK as described in this thesis does, however, appear to be unique. Moreover, the use of a hypothetical compound to approximate waste structure facilitated the application of Monte Carlo techniques to quantify the parametric uncertainty associated with the emissions estimated from using the approach.

Central to the approach used is a mass flow model that approximates the movement of waste fractions through a waste management firm. Associated with each fraction is a unique chemical composition that has been collated from published data sources. Sorting processes in the model essentially act as routers diverting waste fractions to their final treatment process. In these final processes the chemical data is used to determine the hypothetical compound structure used to estimate greenhouse gas emissions. Energy content of waste fractions and RDF is estimated using a modified Dulong equation and that of methane is estimated based on enthalpy of combustion and an assumed efficiency of plant. Estimates of transport emissions are determined from using a regression model that passed relevant statistical tests.

Quantities of waste recycled, recovered, and landfilled as well as energy generated are calculated in the model to determine the performance of the firm against key regulatory targets. These outputs can be used to assist waste management firms with making strategic decisions by comparing the outputs from a number of different treatment scenarios. The performance of each scenario can be contrasted with the carbon footprint of each. Future legislative changes can be introduced by changing the treatment process of specific fractions. For example, promotion of biowaste can be modelled by diverting more organic waste to aerobic or anaerobic degradation processes.

System dynamics was used because of the ease of modelling exponential decay; the stocks and flows used to describe a system is well suited to the research model because it is driven by the flow of waste; and because the system of equations used to describe the model can be constructed graphically rather than expressing the system explicitly in equations. Vensim was selected because it can be driven by data contained in spreadsheets. Furthermore it has built in optimisation and sensitivity analysis suites that negate the need for additional compilers and data conversion.

Credibility of the model was tested using a structured approach. Each test indicated that the model is capable of achieving its primary objective. Furthermore, under extreme behaviour all outputs from the model were plausible, but relied on the credibility of the landfill sub-model, which was verified against GasSim.

Secondary Objectives

Two key pieces of European legislation are linked to waste management and mitigating climate change: the Landfill Directive and the Renewable Energy Directive. Both have spawned UK policy and strategy, but only the former directly relates to how MSW is managed. Energy policy indirectly affects managing waste on the basis that some technologies used to treat waste can also generate energy. The key constraints to managing MSW arising from national legislation are the recycling and recovery targets of the Waste Strategy 2007. The financial incentives of the Renewables Obligation Order also mean that this piece of UK energy legislation is likely to feature in the future strategic decisions of waste management firms.

The contribution to global warming and climate change from managing waste was discussed in Chapter 3, which identified that methane emissions from landfill and transport emissions were of particular importance. Outputs from life-cycle impact assessment discussed in Chapter 5 also highlighted that process emissions from treatment plant and offsets from recycled material would impact global emissions of greenhouse gases. Furthermore, the case study of PenWaste also showed that without materials recycling, managing waste in the UK is unlikely to reduce total greenhouse gas emissions but that it would be likely to reduce emissions of fossil-carbon based greenhouse gases.

Chapter 4 provided a formal definition of a system and showed that this definition was applicable to managing waste. More specifically, a waste management firm could be defined as the system of interest (SOI) that interacted with certain elements of its surrounding environment. Conceptually these areas of interactions form the wider system of interest (WSOI) and include real systems such as government agencies, the economy, etc.

Functional analysis was used in Chapter 5 to define the functions and sub-functions that were necessary to estimate the carbon emissions from managing MSW. Life-cycle impact assessment was used to argue that the emissions profile was dominated by a few key elements that required modelling: transport emissions, landfill emissions, process emissions, recycling offsets, electricity exports and energy offsets. Chapter 6 then showed how these elements were integrated to estimate the carbon footprint from managing MSW on the Black Peninsula. Targeted policy scenarios were used to indicate how different potential strategies could impact the evolution of the carbon footprint.

Chapter 5 identified those processes in a waste management system that dominated the carbon footprint: methane emissions from landfill, transport emissions, combustion emissions, and displaced emissions from energy generation and virgin material substitution. The case study of PenWaste also showed that if biogenic carbon dioxide was included in the emissions inventory, then combustion of waste or waste derived fuels would release more CO_2e emissions than would be emitted from fossil fuels. Recycling of non-ferrous metal and textiles offered the greatest benefit to the carbon footprint by virtue of the size of their emissions factors. Aerobic composting of biodegradable waste released more CO_2 than would be offset from use of the stabilised material as compost. Hence, anaerobic treatment would be favourable because of the energy that can be recovered from the biogas. Parametric uncertainty analysis undertaken in Chapter 6 also showed that the level of methane oxidation in a landfill cap would have a significant effect on the impact of fugitive methane emissions and hence the carbon footprint.

PenWaste was used as a case study to test and verify the model, as described in Chapter 6. Some properties of the real system are replicated in the model along with historical values of emissions and waste handled. Under extreme behaviour all outputs from the model were plausible, but relied on the credibility of the landfill sub-model, which was verified against GasSim. Results from testing the model also suggested that technological improvements in capture efficiency and flaring rates could offer significant reductions in fugitive methane emissions at landfill sites.

Recycling and energy generation scenarios were proposed to reduce the carbon footprint of PenWaste in Chapter 6. A combined policy option in which textiles, metals and glass were recycled and energy was recovered from combustible fractions and organics offered the best compromise in achieving diversion targets, improved recycling rates and increased energy generation whilst maintaining a negative emissions profile. Furthermore, the financial incentives of UK energy policy appear to make reducing the carbon footprint financially viable. Estimated figures based on 2002 costs for anaerobic digestion (AD) and energy from waste (EfW) plant indicated that AD could offer £16 per tonne in revenue and EfW could yield £58 per tonne.

Recommendations for Policy and Practice

The recommendations fall neatly into two types: those relevant to waste management and climate change policy, and those related to existing waste management practice.

Policy

Given that this thesis advocates the use of the systems approach to solving problems, this research has been constrained by legislative drivers; i.e. the focus on MSW, which only accounts for around 10% of total UK waste. Waste itself should not be viewed in isolation as an end-of-pipe solution, as it has in this work. The holistic view is to consider how waste is generated in the first place, what causes it and how it can be reduced. The fact that only 70% of household waste could be recycled if all householders were super-committed highlights this point. Hence the systems approach would be to study how products enter the economy and what drives their consumption. It is recommended that manufacturers of products should be targeted and discouraged from using products that cannot be recycled and that non-hazardous waste is classed under the umbrella term of general waste, rather than the current sector based categories.

As Kyoto targets have been transposed first into EU and then UK legislation, the focus has seemed to have got misplaced. As a result, greenhouse gas mitigation has been assigned proxies such as biodegradable municipal waste or renewable energy. The analysis undertaken in this thesis has illustrated that use of waste management technologies for energy generation is likely to release more carbon dioxide per MWh of electricity generated than fossil fuel sources. The problem arises when all renewable energy targets have been met but carbon dioxide emissions have increased, which is counter to the ethos of Kyoto. It is therefore recommended that all proxies for greenhouse gases be revisited and re-evaluated to ensure that this emissions pseudo-paradox cannot occur elsewhere. Targets need to be directly related to the problem of global warming and climate change, which are currently greenhouse gases – but even this method is not fool proof, particularly if NOx and CO are assigned GWPs in the future.

Rethink Methane Mitigation

The existing legislative regime of regulating the quantity of biodegradable municipal waste going to landfill means discounting the possibility of using landfill bioreactor technology for stabilising large quantities of organic material. The methane released during the process can be utilised to generate electricity and the heat produced can be re-circulated to maintain optimum yield temperature. This approach can accommodate large quantities of biowaste that can be excavated once gas production has diminished and the waste material has stabilised. As shown with the PenWaste case study, anaerobic degradation is preferential to aerobic if the biogas is used to generate energy – this is not possible with aerobic composting. A further advantage is that much of the carbon in the waste remains in the stabilised material in contrast to combustion in which the majority of carbon is released. It is therefore recommended that the Landfill Directive is reviewed and the methane mitigation measures redefined in terms of global greenhouse gas emissions rather than the current parochial view.

Define Carbon Neutral

Climate change and global warming is clearly not well understood in the waste sector. If it was, then the waste management greenhouse gas protocol would not discount emissions of biogenic carbon. Hence there is a need to formally define the term *carbon neutral* so that levels of carbon dioxide in the atmosphere are reduced. The current accepted criterion for a carbon neutral fuel is essentially a fuel that is not derived from fossil sources.

The issue with this is that releasing CO_2 in to the atmosphere, biogenic or not, it will still absorb infra red radiation and contribute to global warming. Reducing the impact of global warming means reducing the amount of CO_2 in the atmosphere or at least stabilising its concentration. This means that the rate of emission must equal the rate of removal or sequestration: if CO_2 is removed from the atmosphere at the same rate as it is released into the atmosphere then the atmospheric concentration will be stable. Hence any activity that causes no net change in global atmospheric greenhouse gas emissions should be defined as *carbon neutral*. In a global context, the focus of policy should be on reducing the emissions rate and increasing the removal rate of greenhouse gases.

Practice

This thesis has shown that by considering waste in fractional form, particularly its chemical fractions then appropriate treatment processes can be objectively identified. Therefore other waste streams can also be managed using this approach, particularly commercial waste and general industrial waste which are similar in composition to MSW. Thus compatible waste fractions from each stream (e.g. paper and card) could ultimately be co-processed, which would have significant financial benefits as well as environmental ones. Hence there is a need to standardise the contents of waste sub-categories and create a chemical composition database for each, similar to PHYLLIS (ECN, 1997), but specifically for UK waste streams.

Regular monitoring and reporting of waste on a compositional basis would make carbon footprint modelling much easier and likely improve its accuracy. Furthermore, it would also help facilitate measuring the performance of waste management systems. The existing approach is for local authorities to report waste recycling data, for example, centrally via Waste Data Flow. These data can be easily accessed and used to compile statistics on tonnages of glass recycled, etc. But because the initial proportion of glass in the waste stream is not known, it is not possible to assess if that particular local authority is recycling 5% or 50% of the glass. Whereas monitoring waste fractions arising would enable much more useful statistics to be gathered, particularly pertinent to carbon offsets. Local authorities should, therefore, be tasked with conducting regular surveys to determine waste composition in their region. In the future, this would enable trends in waste fractions to be identified and projected forward to assess impact on current waste management strategy and practices.

Limitations of the Approach

Although the hypothetical compound method is flexible and easy to use, modelling pyrolysis, gasification, and autoclave technologies have not been included in this approach. Tchobanoglous et al. (1993) suggests a reaction scheme for the pyrolysis of cellulose which could be modified to use with the hypothetical compound but the physical products are temperature dependent. However, this was considered beyond the author's knowledge and expertise and hence is why these modules have not been included in the model. For future strategic decisions, these processes would need to be included in any analysis, which makes the current configuration of the model impractical. However, given that these technologies are still in their infancy, and that other more established technologies (such as anaerobic digestion or incineration) are eligible for green energy subsidies, it is unlikely that waste management firms will invest in these fledgling processes in the short-term.

Lack of consistency in units used to report waste transported by firms makes it difficult to convert between waste arisings, reported in tonnes, and waste transported, reported in cubic metres. Consequently, the development of the fuel model restricts the estimates of the transport emissions to the current configuration of WasteCo's vehicle fleet. It is also a very highly attenuated linear model because it lumps together truck type, truck age, load factors, distances, etc. into one parameter. Although the model can be calibrated to historical data it can only estimate fuel use and hence the effect of changing vehicle characteristics or journeys cannot be modelled. Thus should significant changes in fleet composition arise, such as the introduction of hybrid vehicles, then the estimates from the fuel model would be inaccurate. Impact of biofuels use, however, can be estimated by adjusting the emissions factor associated with diesel combustion.

Despite identifying the role of indirect greenhouse gases in methane's removal chemistry and noting that these gases are present in combustion products of diesel engines, landfill gas engines and other combustion plant, constraints on time, data, and expertise did not permit the inclusion of these findings in the model. Furthermore, there appeared to be (at time of writing) no general consensus on the importance of indirect greenhouse gases, let alone how to estimate their global warming potential, so this area was considered beyond the scope of the research.

Capturing historical data more aggregated than tonnes of MSW has been difficult because there is no requirement for waste management firms to report waste on a fraction by fraction basis, so input to a facility (e.g. RRF on Black Peninsula) is recorded in tonnes. Waste leaving the plant can be categorised as fines, rejects, recyclables etc. This makes compositional analysis almost impossible so many assumptions have to be made regarding how incoming waste fractions populate these outputs. Furthermore, there is always an increase in the fine fraction leaving a treatment facility (particularly if a ball or hammer mill has been used as part of the treatment process). This introduces further uncertainty into the analysis since it is difficult to determine accurately which fractions have become fines. Although this was 'backed out' from the data and sensitivity analysis was undertaken to estimate the impacts of the assumptions, sampling of waste streams into and out of plant would greatly reduce this uncertainty.

Waste composition and ultimate analysis data are scarce. This research has tried to improve this lack of data by collecting, collating, and statistically analysing European and US waste data to gain some insight into the likely chemical composition of each fraction. However, this has indicated that some fractions exhibit large variances due to the range of different materials that fall into certain categories, e.g. the combustibles fraction contains wood, leather, furniture, etc. Despite crude allocation of materials data to fractions (e.g. carpet grains as combustibles) the process has proved useful in identifying key waste fractions that impact the chemical composition of waste streams. Had the national household waste analysis programme (NHWAP) not been disbanded, a huge amount of waste data would be available for use and would have likely reduced the uncertainty associated with waste composition. But this gap in data is not unique to this thesis; the chemical data related to each waste fraction used in the Environment Agency's LCA tool, WRATE, is based on the NHWAP data set from 1994.

Directions for Further Work

Areas for further work include in particular, developing a waste generation module that can estimate waste arising based on social class, and optimising the model such that energy generation can be maximised whilst achieving 2020 recycling targets.

Waste Generation Module

During the course of this research it has become apparent that waste generation is a complex process and whilst being related to demographics it is also related to the products that enter the home, i.e. householders can only discard items that they purchase – householders do have some choice, such as whether to buy products with recyclable packaging or not, or to cook using ingredients, rather than buying ready meals. But ultimately, if there is a dramatic shift in the type of packaging used, e.g. plastics are synthesised from cellulose or deposit bottles replace existing stock of plastic bottles, then the waste composition will change but the types of consumers may not. Hence developing a model that relates consumerism to waste generation would be an incredibly useful piece of work and tackle the waste issue at source – as materials enter the economy.

Inclusion of other Waste Streams

Industry supplies society with goods and services, and in the process generates waste: this may be process specific like mining waste or it may be general waste composed of packaging materials, food, etc. that require no specialist treatment. These goods and services are then consumed by society, which ultimately leads to waste being generated. This consumption is related to social class and hence influences waste composition because households can only discard items that they import. Indeed, socio-economic groups may also influence the composition of commercial waste streams. Certain groups may frequent pubs and bars causing "waste glass" to be generated in the commercial sector, whereas other groups may drink at home causing "waste beverage containers" to be generated at the household. This could be further extended in that social class may even influence the type of beverage container discarded, e.g. aluminium cans (beers and cider, etc.) compared with green bottles (wine). Hence there is a real need to understand how social class and demographics are linked to consumerism and hence to waste generation.

Industrial waste is also directly linked to consumerism. By assessing the composition of all of these streams in terms of primary waste categories (rather than the current sector based categories) coupled with a consumer-behaviour based generation model, would allow the process emissions to be estimated for a significant proportion of UK waste using the Research Model in its current configuration. Furthermore, this has the potential for maximising the efficiency of a waste management system by being able to choose the most appropriate technology relative to the waste fractions arising.

Progress made by government agencies in identifying waste composition on a SIC code basis will make this easier in the future. And most general industrial waste is likely to be able to be treated using MSW technologies. Process specific waste may not, but considering waste as a collective entity comprising different fractions, each with a specific chemical composition would improve efficiency in managing waste. It would also enable these wastes to be included in the model, which could then be used to estimate a firm's total carbon footprint, rather than from MSW contracts.

Development of Additional Process Modules

Gasification and pyrolysis processes were not included in the model. The rationale for this was that they were fledging technologies operating at the pilot scale when the research commenced. However, as this thesis was being completed, the pyrolysis plant on the Black Peninsula was commissioned and as this plant matures much useful data can be gathered to facilitate a model being developed and tested. Also, these technologies will receive subsidies for generating energy under the Renewables Obligation Order. Hence developing modules that can approximate these processes would greatly improve the model described in this thesis and allow it to evolve whilst maintaining its ability to inform strategic decisions.

As with the existing processes in the model, the composition of the waste will still determine products from the process, i.e. syngas, char, oils. However, the quantities and proportions of these products are temperature dependent and therefore will most likely be more complicated to estimate using a hypothetical compound.

Impact of Indirect Greenhouse Gases on Methane Removal

A system dynamics model of the life-cycle of methane that includes the tropospheric removal scheme would help identify the relative importance of the parameters involved and also determine the magnitude of the influence that indirect greenhouse gases have. Conclusions from this type of analysis would inform the carbon footprint debate by favouring those processes that promoted methane removal from the atmosphere as this would reduce its global warming potential.

Optimisation of the Model

The model in its current form can has been used to show that the carbon footprint of PenWaste could be reduced. The strategy proposed also showed that it was possible to reduce carbon emissions whilst contributing to renewable energy targets and improving recycling and recovery rates. However, an optimum solution would be to maximise energy generation whilst achieving recycling targets. The number of potential configurations of diversion rates that could achieve this in the model is enormous, so optimisation is the next sensible step for the model. Optimising the distribution of waste fractions in this manner is extremely powerful, because it determines the sorting strategy necessary to minimise the carbon footprint.

Scale Model to the UK Level

The model in its current form can estimate the carbon footprint of MSW management contracts. Scalability seems plausible because of the methods used to estimate emissions. Because the hypothetical compound structure seems to remain constant, this implies that the chemical composition of waste is also fairly constant. Consequently, the carbon available to be released into the atmosphere is also constant, and as shown in the thesis, the quantity actually emitted is process dependent.

It follows then, that the scalability of each process will determine how well the model itself can be scaled. An example of this is greenhouse gas emissions from landfill sites. The methane generating potential of waste is determined by the properties of waste discarded. Although the chemical composition may be similar across the country, the quantity of degradable organic carbon may not be and hence the methane generating potential may vary. Furthermore, the required flow rates for utilisation of landfill gas may not be reached at all sites in the UK. So as a result, some regions will generate more electricity per tonne of waste landfilled than others. Hence understanding how the processes in the model can be scaled would determine if the model could be used to estimate the carbon footprint from managing UK waste.

Conclusions

Approximating waste streams as hypothetical compounds coupled with using Monte Carlo techniques to quantify parametric uncertainty is a robust method of estimating the dominant greenhouse gas emissions arising from managing MSW.

Waste structure is fairly consistent in chemical composition, even under intensive recycling programs. Hence MSW contains similar amounts of carbon per tonne, on a dry basis. Therefore it is the treatment process that will determine the quantity and severity of emissions.

Waste management firms are well placed to reduce global greenhouse gas emissions, but it is likely to be to the detriment of national emissions inventories. However, recovering energy from waste is unlikely to reduce emissions of greenhouse gases in the energy sector.

Energy policy is likely to compromise the greenhouse gas reduction potential of the waste management sector because of the lucrative opportunities arising from generating renewable energy. However, it is likely that UK recycling and recovery targets can be met via an optimised diversion strategy that would reduce UK dependence on fossil fuels as an energy source but it would also preserve their use for future generations.

Carbon neutrality requires a formal, internationally accepted definition that embraces the science underpinning global warming. With this in place, firms should be encouraged to minimise their global emissions profile

A pragmatic approach to managing MSW is required. The fact that only 70% of household waste could be recycled if all householders were super-committed highlights this point. Waste itself should not be viewed in isolation as an end-of-pipe solution: how products enter the economy and what drives their consumption needs to be the focus of future waste management research.

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