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# Hidden flows and waste processing in a domestic economy – an analysis of illustrative futures

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## Abstract

An existing materials flow model is adapted (using Excel™ and AMBER™ model platforms) to account for waste and hidden material flows within a domestic environment. Supported by national waste data, the implications of legislative change, domestic resource depletion and waste technology advances are explored. The revised methodology offers additional functionality for economic parameters that influence waste generation and disposal. We test this accounting system under hypothetical future waste and resource management scenarios, illustrating the utility of the model. A sensitivity analysis confirms that imports, domestic extraction and their associated hidden flows impact mostly on waste generation. The model offers enhanced utility for policy and decision makers with regard to economic mass balance and strategic waste flows.

**Keywords**: waste, resource, management, material flow analysis, modelling, accounting.

## 1. Introduction

It is widely accepted that the current rate of extraction and consumption of finite global resources is unsustainable, and associated with global warming, unsustainable depletion of fossil fuels and, on occasion, localised damage to the natural environment [1]. Of course economic growth, which usually correlates positively with increased resource extraction and utilisation, is also associated with increased employment, greater societal access to goods and services and higher standards of living. A key challenge for the 21st Century is to decouple resource consumption from economic growth. One strategy for closing this gap [2] must be in implementing more sustainable patterns and behaviours of production and consumption [3, 11]. National environmental policies increasingly focus on the twin goals of improving resource productivity and eco-efficiency. Whilst the former relates the material and energy inputs of production to final industrial output, the latter relates industrial output to the immediate ecological impacts [4, 5]. The more mature resource strategies have the higher ambition of 'dematerialisation'; that is, a progressive reduction of material use. Japan and Germany [6], but also the European Union more broadly, are exploring and partly enacting such resource policies [7].

The macro analysis of material flows in an economy has been one means of informing these policies. Tools for materials flow analysis have developed out of associated techniques for relating resource-use to environmental impact. For instance, life cycle assessment (LCA) is one means of tracking resource use (usually in products) from "cradle to grave". LCA is usually limited to a single production process, is complex and data intensive for multiple products or a whole economy, and so ecological footprinting has been used in an attempt to collapse multiple environmental impacts into a single sustainability indicator [8]. Hybrids also exist. Zhao, Li, and Li [9] developed a method that starts from assessing the energy flows of a socio-ecological system alongside its biological productivity. Others have considered the flow of carbon during waste generation [10] and the wastes generated within manufacturing processes [11]. These tools have been used to infer the sustainability of a domestic economy in its current state, but do not generally allow the forecasting of alternative scenarios in the way some hybrid input-output tables do [17]. Given the pace of change in the UK with respect to waste and resource management, we have perceived a need for a flow model capable of forecasting resource use and waste generation under different economic and social conditions. Accordingly, this paper augments an existing materials flow model for the UK economy that relates material flows to waste generation. Scenarios are introduced in order to explore the model, the results and implications of which are discussed.

## 2 Method and model development

There are two elements of the methodological approach used in this study. The first is the development of a material flow model with commonly available software (spreadsheet Excel™; mass flow model platform AMBER™); and the second is the construction and exploration of illustrative future scenarios for discussion. Waste flows in the UK economy can be conceptualised as a materials cycle which, as Matthews *et al.* [13] have explained in depth, involves a number of inputs flowing through a domestic economy and its associated environment. In brief, direct material and energy input (DMI) enter an economy for economic processing (Figure 1) either as imported raw materials or as domestically extracted resources.

(insert Figure 1)

In doing so, these inputs add to the national resource stock, which comprises goods, buildings and infrastructure, thus representing a net addition to stock, NAS. As a result the maintenance of the economy is secured and output produced - exports are sent aboard and domestic processed output (DPO) are goods retained within the domestic environment. For the domestic environment, as these goods fall out of the chain of utility, they generate domestic waste streams and thus waste mass (in millions of tonnes, Mt) for waste processing through a range of technologies.

Imported and domestic inputs also have associated ‘hidden flows’ that result from extraction and processing. Hidden flows are often referred to colloquially as those materials extracted during production, but that are not actually used in the product themselves. An example of a domestic hidden flow is the material disturbed (overburden) when minerals are extracted from quarries in the UK; for example during china clay extraction. Hidden flows are significant because whilst they may not be accounted for in conventional resource management models, they often have significant environmental impacts because their mass, or volume, may be considerably greater than the material requirement of the product in question. In brief, hidden flows do not enter the realm of economic processing. They are categorised (Figure 1) by whether they enter the domestic environment from abroad (foreign hidden flows, FHF), or as a result of domestic resource extraction (domestic hidden flows, DHF). Taken together and considered alongside the domestic material input (DMI), they constitute the total material requirement (TMR) of a domestic economy, say the UK. Together, the total hidden flows (DHF) and the domestic processed output (DPO) from economic processing represent the total domestic output (TDO) of the economy (Figure 1; [18, 34]). These concepts are now in wide use and the concept of hidden flows has been adopted to illustrate the hidden impacts of waste generation [14, 15, 35, 36]. This conceptual framework (Figure 1) has guided the construction of the materials flow model in our work [37, 38].

Our concern here relates to hidden flows and waste generation [38]. The first stage in building a quantitative model was to identify and term the variables involved. Bringezu and Schütz [16] demonstrated the domestic material input (DMI) is the main input variable in these models. In order for the model to detail the constituent components of the DMI, as well as the fate of the materials as outputs which is important for considering waste management implications, a number of sub-variables were required. These were adapted from Bringezu and Schütz [16] performed for the Department for Environment, Food and Rural Affairs (Defra, in England) and are explained in Table 1.

(insert Table 1)

A fundamental assumption concerns the hidden flows. Given our model's primary concern with waste flows it was assumed that those fractions of the hidden flows that enter the domestic environment remain unaltered and as such were represented by a simultaneous input and output. Hence, only the direct waste streams resulting from the FHF were considered here. In order to explore future waste flows, model assumptions are required with respect to domestic processed output (DPO) and total domestic output (TDO), including the generation of specific waste streams (Figure 1). To this end, disposal routes were selected and sectoral waste generation data (2006) employed by the Environment Agency [20]. The total of *ca*. 434 million tonnes (MT) of waste arisings were disaggregated ($^{w}/_{w}$) into: 20% agricultural wastes, 21% mineral wastes, 8% dredging, 8% municipal wastes, 13% industrial wastes, 6% commercial wastes, and 24% construction and demolition wastes. Sewage sludge was estimated at contributing < 1% of the wastes produced in the UK and for the illustrative purposes of simplifying the modelling calculations, was assumed to be zero.

With the wastes designated in the model (Figures 1 to 3) it was necessary to complete the description with the disposal pathways for each of the wastes. The data on disposal routes was compiled using figures predominately from the Environment Agency [21] with supporting data from Defra [22, 23] and, in the case of dredging, from Morris [24]. Simple linear flow models representing the linear flows in Figure 1 were constructed both in Excel™ and in the mass balance platform AMBER™.

## 2.1 Scenario development

The modelling approach employed a baseline scenario representing the current economic metabolism of the UK (2006) and its growth based on the status-quo. Against the baseline case, the implications of three alternative scenarios were modelled; thus the four scenarios modelled were: (i) the baseline scenario; (ii) a scenario in which the UK runs out of domestic resources; (iii) a scenario reflecting legislative changes in the UK; and (iv) a technologically advanced future. Assumptions that characterised these illustrative futures were used to amend the model parameters adopted for the baseline scenario, and the results generated, reviewed and discussed.

### *The baseline scenario*

The baseline scenario acted as the reference that all subsequent scenarios were compared against, representing a relatively accurate picture of the 2006 situation within the UK. The model inputs, including the direct material inputs (DMI) to the model, were adapted from Enviros Consulting [25]. Three time intervals, used for all scenarios, were T1: 2010; T2: 2015; T3: 2020.

### *The UK runs out of domestic resources*

The second scenario is a future in which resource issues become a significant problem for the UK, at a time when it experiences poor economic growth. As Enviros Consulting [25] state, the majority of the UK's resources are imported. The former government Department of Trade and Industry [DTI; 26] elaborated on the decline of the UK's indigenous energy supplies the associated economic consequences. The DTI stated that the UK will have run out of its indigenous energy supplies within a decade and, by 2020, be dependent on other countries for three quarters of its energy needs. This outlook is expected to impact directly on the composition of material flows. The variables requiring alteration in this regard against the baseline scenario ($^{w}/_{w}$) were a decline in domestic extraction (T1: 45.0%, T2: 31.2%, T3: 14.0%,) and subsequent increase in imports (T1: 55.0%, T2: 68.8%, and T3: 86.0%).

***Legislative changes to waste policy***

The legislation of wastes is a hugely dynamic domain with the frequent introduction of new regulations and the continual revisions of existing directives and targets. The Chartered Institute of Wastes Management [27] outline some of the key legislative advances in recent years. These have been carried forward by the legislator and elaborated on in the Waste Strategy for England [28]. England has targets for recycling and composting, waste recovery and landfill diversion, these supported by (among other regimes) the Landfill Tax escalator the Landfill Allowance Trading Scheme (LATS). Using the above information on regulatory regimes, a small number of changes to the variables, compared with the baseline, were made for this scenario. According to an EU study [29] biodegradable municipal waste (BMW) accounts for between 60% and 70% of municipal solid waste (MSW) and as such the change in the landfill variable was based on this and the targets identified above. Thus the proportion of MSW going to landfill was adjusted ($^{w}/_{w}$) from T1: 48.7%, to T2: 24.4% to finally T3: 6.1% while the amount processed by other disposal routes increased ($^{w}/_{w}$) by T1: 26.3%, T2: 50.6%, and T3: 68.9%. The legislative changes did not affect the broader economic scale variables, which remained the same as for the baseline scenario.

***A technologically advanced future***

This scenario assumes an optimistic future for the UK economy based on sustained economic growth, the long-term security of domestic resources and energy supply and technological innovation that allows resources to be harnessed with increasing resource efficiency. Importantly for modelling this scenario, developments in the new waste technologies are assumed to be moving apace. Technologically advanced and innovative methods for efficient recycling and recovery become the key solutions to landfill diversion, which is then utilised predominantly used for process residuals and materials with no further use. This is translated into a series of illustrative changes to the baseline variables presented in Table 2.

(insert Table 2)

# 3 Results

The baseline assumptions on resource flow and resulting tonnages of waste flowing through various disposal routes in the baseline scenario are presented in Table 3. All other scenarios are discussed against this baseline data set. Where a change in certain variables does not require new data, the default values were those adopted in the baseline scenario. These waste management futures are illustrative and somewhat artificial in construct, though they do provide a valuable basis for discussing future implications below.

(insert Table 3)

## 3.1 The baseline scenario

Prior to discussing individual scenarios, a sensitivity analysis of the model was undertaken, illustrating the sensitivity of various model output variables to changes in input data on the baseline scenario. The key economic parameters were altered in sequence (Table 4), adopting a 10% increase on the baseline value in each case.

(insert Table 4)

The dominant parameter and one to which all others were most sensitive, as expected [19], was DMI input. A 10% increase in DMI generated a change of 642 Mt with the most significantly effected parameters being domestic extraction (+100 million tonnes) and TDO (+200 million tonnes). Imports and domestic extraction also exert a direct impact on DHF and FHF. A 10% increase in these parameters exerts significant changes in the other variables. The sensitivity of individual parameters was low but the overall impact is shown to be significant, as represented by the 295 MT variance for imports and the 596 MT variance for domestic extraction (Table 4). The variation experienced for imports and domestic extraction are limited since they are directly dependent on DMI. The domestic parameters of NAS, DPO and exports are only influenced by the DMI value. Overall, it is evident that DHF and FHF are extremely sensitive, which is an important observation given their interest here.

### 3.2 The UK runs out of domestic resources

Here (Table 5), the main change from the baseline scenario is an increase in foreign hidden flows (940 Mt) resulting from growing imports. In contrast to the baseline, imports and FHF double in quantity. Interestingly the FHF now make up 62% of the original DMI and would eventually surpass this figure if the trend shown continued. Domestic extraction falls by 467 Mt, resulting in a total reduction, over T1-T3, of 281 Mt for domestic hidden flows (DHF). As a result of these impacts the total domestic output (TDO) of the UK increases by 659 Mt with a total over the three time intervals of 8346 Mt; a 39% increase on the baseline.

(insert Table 5)

### 3.3 Legislative changes in the UK

This scenario highlights the changes that occurred through the time period of the model under this scenario, relative to the baseline. The changes generated by the model are rudimentary and touched on here only briefly. Most critically, with mandatory legislative targets in place, the amount of municipal waste going to landfill decreases by 68 Mt while other disposals subsequently increase by 69 Mt [37]. The overall (T1-T3) increased tonnage of wastes through other disposal routes, representing that amount diverted from landfill, is 234 Mt over the T1-T3 period. Inevitably, this raises the issue of how and where to treat the increased amounts of biodegradable municipal waste. The UK is already on a strategic trajectory toward a more technologically advanced future, at least with respect to implementation of the new waste technologies, and so the key scenario of interest here follows.

### 3.4 A technologically advanced future

Here (Table 6), the domestic extraction and net addition to the economic stock (NAS) increased by the greatest quantity, 640 Mt and 560 Mt respectively, which in turn were 74% and 62% greater than the baseline. This highlights the influence of a growing economy together with the presumption of newly obtainable domestic resources. DPO decreases by 99 Mt, however; the growing DMI acting as a limiting factor. The reduction in FHF is now a direct result of the decreasing reliance on imported materials. Even though in this scenario the UK secures domestic resources in the long term and the economy is assumed to grow, the environmental impact from TDO is likely to remain. Here, we also assume technological advancement in implementation of the new waste management technologies (Table 6). These new technologies are assumed to experience growth over the modelling period with significant declines in landfill and other disposal routes at 152 Mt and 246 Mt respectively. This scenario also assumes a substantive reduction in waste from agriculture and dredgings. The remaining waste treatments see moderate increases in tonnages treated. Furthermore, the total tonnage treated is also reduced relative to the baseline by 497 Mt (30%).

## 4 Discussion

The coding of a rudimentary resource flow model in Excel™ and AMBER™ platforms illustrates that resource flow can be coupled to waste generation and management at the macro level [37]. Flexibility allows the examination of a wider range of disposal routes over time, providing the national treatment capacities and statistics are known. There remain data gaps with regard to quantifying hidden flows. As these can have significant impacts on the economy and environment it is crucial these are well represented in the model. Although the model was constructed as closely as possible to the materials cycle represented in Figure 1 [18, 19], there were areas that were excluded because of their complexity; e.g. the UK's NAS should take into account a certain degree of outflow due to end-of-life products and buildings that are removed from the chain of utility as wastes. Furthermore, the materials cycle detailed by Matthew *et al.* [18] included air and water as part of the material flows. Omitting air, whilst acceptable here for the handling of solid wastes flow, may be a critical deviation from material flow analysis in a broader context of applications because it distorts the accuracy of carbon counting.

Given these provisos, model improvements are clearly possible. The decay in stock, excluded from the model could be researched and a reliable figure provided so that an inward flow and outward flow could be attributed to stock giving a more accurate overall picture.

Similarly, the disaggregation of waste by disposal route could also be refined, which we expect would be particularly useful for local authorities seeking to model future waste management strategies because short falls in available capacity could be identified in this way.

Carbon and energy flows are of increasing importance in the waste and resource management sector as Uihlein *et al.* [30] and Biffaward [15] explain. Developments into these areas and disaggregating them within the tool, would be of significant use. Advancements can always be made by improved data to use in the tool. Users will have the option to do this anyway but by improving the underpinning data behind the model's calculations the general accuracy and reliability of the tool will be improved. Users could chose to focus on specific waste types such as biodegradable waste or focus on new technologies such as pyrolysis, gasification or plasma treatment.

Though the socioeconomic scenarios were not produced for their own sake and the general limitations of materials flow accounting apply to this model; *i.e.* they do not provide information on economic development at the business sector level [31], the development of the tool has still provided insights into alternative development strategies for the UK economy. The impacts in the depleting-resource scenario will not be restricted to the UK [32]. As these illustrative results have shown, the growth in imports may also increase foreign hidden flows (FHF) and shift the environmental burden of resource extraction abroad. This is a further component to the issue of hidden flows, already recognised by non-governmental organisations seeking to highlight the implications of waste transported overseas for processing in other nations [35]. As the number of trading partners the UK requires increases, the environmental impacts already occurring in other countries may be compounded in response to the UK's higher demands. Unless the trading partners could increase their extraction efficiency and/ or process their resources with higher eco-efficiency prior to export, an increase in FHF would occur. Environmental pressures would also increase in the UK if economic growth continued but in addition to growth the UK's environmental burden would become twofold and expand to that of the trade partners.

The results from the technologically advanced scenario illustrate a positive development for the UK supporting the analysis of Berkhout *et al.* [34], who also suggested that unemployment in a case like this would be low, income would be medium to high, and equity would improve. However, they also pointed to a potential conflict that could arise from the change of skills required for such innovation. Nevertheless, of the scenarios explored in this analysis, this might appear as the ideal path for the UK. The expectation is now that the UK will develop and use more material- and eco-efficient technologies to support the transition to a low carbon future. National, regional and local assessments of hidden flows in the economy [36] will be an important input to informed decisions by the full range of actors (local authorities, operators, regulators, citizens; [37-39]) on materials management.

## 5 Conclusion

In developing an integrated modelling tool for assessing and specifying the UK's material and waste flows this research has accomplished its key objective. The modifiable nature of the parameters in the tool means that specific waste types can be targeted or alternative technologies used and for any time period. Thus, the tool can potentially support decision-making for resource management as the customisable nature of the model makes it potential valuable across a full range of scales. Since the model is effectively visualised with built-in validity checks it can be fully modified to suit user requirements.

The illustrative scenarios explored here, demonstrate the considerable fluctuations in actual and hidden material flows that can arise from the extremes of reliance on foreign or domestically extracted materials. Clearly the results are illustrative alone and can not yet, be used to infer actual short term fluctuations, but they can be used to initiate a discussion on the capacity requirements of the new waste technologies in the UK.

## References

[1] Environment Agency, *Delivering for the environment*, http://www.environment-agency.gov.uk/business/444217/444661/571853/, accessed May 2006.

[2] P. Ekins and S. Sandrine, *Estimating sustainability gaps: methods and preliminary applications for the UK and the Netherlands*. Ecological Economics 37 (2001), pp. 5-22.

[3] A. Tukker, S. Emmert, M. Charter, C. Vezzoli, E. Sto, M. M. Andersen, T. Geerken, U. Tischner, S. Lahlou, *Fostering change to sustainable consumption and production: an evidence based view*. Journal of Cleaner Production 16 (2008), pp. 1218-1225.

[4] A. Smith, A. Stirling, and F. Berkhout, *The governance of sustainable socio-technical transitions*, Research Policy 34 (2005), pp. 1491-1510.

[5] M. Jänicke. *Ecological modernisation: new perspectives*, Journal of Cleaner Production 16 (2008), pp. 557-565.

[7] B. Bahn-Walkowaik, R. Bleischwitz, S. Bringezu, M. Bunse, M. Herrndorf, W. Irrek, M. Kuhndt, T. Lemken, C. Liedtke, T. Machiba, *Resource Efficiency: Japan and Europe at the Forefront*. Wuppertal Institute, Wuppertal. 2008.

[8] COM. *Thematic Strategy on the sustainable use of natural resources*. Brussels, 2005

[9] P.S. Phillips, P. Clarkson, J. Adams, A.D. Read and P.C. Coggins, *County Waste Minimization Programmes: A case study for Northamptonshire, UK*. Sustainable Development, 11 (2003), pp. 103-118.

[10] E. Gentil, T. H. Christensen and E. Aoustin. Greenhouse gas accounting and waste management. in: Waste Management & Research (2009) 27, pp. 696–706

[11] EEA, *Sustainable use and management of natural resources*, Copenhagen, 2005.

[12] A. Adriaanse, A. Hammond, S. Bringezu, Y. Moriguchi, E. Rodenburg, D. Rogich, H. Schütz, *Resource flows: the material basis of industrial economies*. Washington, DC: World Resources Institute, 1997.

[13] J. Barret, *An Ecological Footprint of the UK: Providing a tool to measure the sustainability of local authorities*. Stockholm Environment Institute, Stockholm, 2003.

[14] S. Zhao, Z. Li and W. Li, *A modified method of ecological footprint calculation and its application*, Ecological Modelling, 185 (2005), pp. 65-75.

[15] Biffaward, *Carbon UK*. University of Oxford, Oxford, 2002.

[16] C. Hicks, O. Heidrich, T. McGovern and T. Donnelly, *A functional model of supply chains and waste.* Production Economies. 89 (2004), pp. 165-174.

[17] E. Dietzenbacher, *Waste treatment in physical input–output analysis*, Ecological Economics 55 (2005), pp. 11-23.

[18] E. Matthews, C. Amann, S. Bringezu, M. Fischer-Kowalski, W. Hüttler, R. Kleijn, Y. Moriguchi, C. Ottke, E. Rodenburg, D. Rogich, H. Schandl, H. Schütz, E. Van Der Voet and H. Weisz, *The Weight of Nations: Material outflows from industrial economies*, World Resources Institute: Washington DC, 2000.

[19] S. Bringezu and H. Schütz, *Total Material Resource Flows of the United Kingdom*. Defra, London, 2001.

[20] Environment Agency, *Waste an overview: Waste produced by sector in the UK*, http://www.environment-

agency.gov.uk/commondata/103196/waste2?referrer=/yourenv/eff/1190084/resources_waste/213982/152399, accessed July 2006.

[21] Environment Agency, *Strategic waste management information 2002-3*, http://www.environment-agency.gov.uk/subjects/waste/1031954/315439/923299, accessed July 2006.

[22] Defra, *E-Digest Statistics about: Wastes and Recycling: Sewage sludge*, http://www.defra.gov.uk/environment/statistics/waste/wrsewage.htm., accessed July 2006.

[23] Defra, *E-Digest of Environmental Statistics: Industrial and commercial waste arisings by waste type and management method, 2002*, http://www.defra.gov.uk/environment/statistics/index.htm, accessed July 2006.

[24] R. Morris, *Ports and the Habitats Directive: A UK perspective of port-related dredging*. English Nature: Peterborough, 2006.

[25] Enviros Consulting Limited, *Strategic waste and resources think piece*. Enviros Consulting Limited, Shrewsbury, 2006.

[26] DTI, *Energy white paper: Our future creating a low carbon economy*, The Stationary Office, London, 2003.

[27] CIWM, *Energy from waste: a good practice guide*. IWM Business Services Ltd, Northampton, 2003.

[28] DEFRA, *Waste Strategy for England 2007*, The Stationery Office, London, 2007.

[29] EU, *Biodegradable waste*, http://ec.europa.eu/environment/waste/compost/index.htm, accessed July 2006.

[30] A. Uihlein, W.-R. Poganitez and L. Schebek, *Carbon flows and carbon use in the German anthroposphere: An inventory*. Resources, Conservation and Recycling, 46 (2006), pp. 410-429.

[31] S. Giljum, *Material Flow-Based Indicators for Evaluation of Eco-Efficiency and Dematerialisation Policies*, P. Lawn, Edward Elgar, Cheltenham, 2006, pp. 376-398.

[32] Defra, *Resource use and efficiency of the UK economy*. Defra, London, 2002.

[33] Environment Agency, *Waste technology data centre,* http://www.environment-agency.gov.uk/wtd/679004/, accessed July 2006.

[34] F. Berkhout, J. Hertin and A. Jordan, *Socio-economic futures in climate change impact assessment: using scenarios as 'learning machines'*. Global Environmental Change, 12 (2002), pp. 83-95.

[35] Greenpeace. *Toxic Tech: Not in our backyard. Uncovering the hidden flows of e-waste*. (2008), 11pp.

[36] Stepping Forward. *A resource flow and ecological footprint analysis of the South West of England* (2005) available at http://steppingforward.org/rf/hidden.htm <<accessed 11th December, 2009>>

[37] T. Raffield, *Modelling materials and waste flows in the domestic economy,* MSc thesis, Cranfield University, 2006.

[38] T. Raffield, M. Herben, S. Billington, P. Longhurst and S. Pollard, *Coupling hidden flows and waste generation for enhanced materials flow accounting*, Communications in Waste and Resource Management 8(1) (2007) pp. 12-18

[39] F. Schiller, *Linking flow and energy analyses and social theory*, Ecological Economics, 68 (2009) pp. 1676-1686

Figure 1. The advanced materials cycle (after [18], [34])

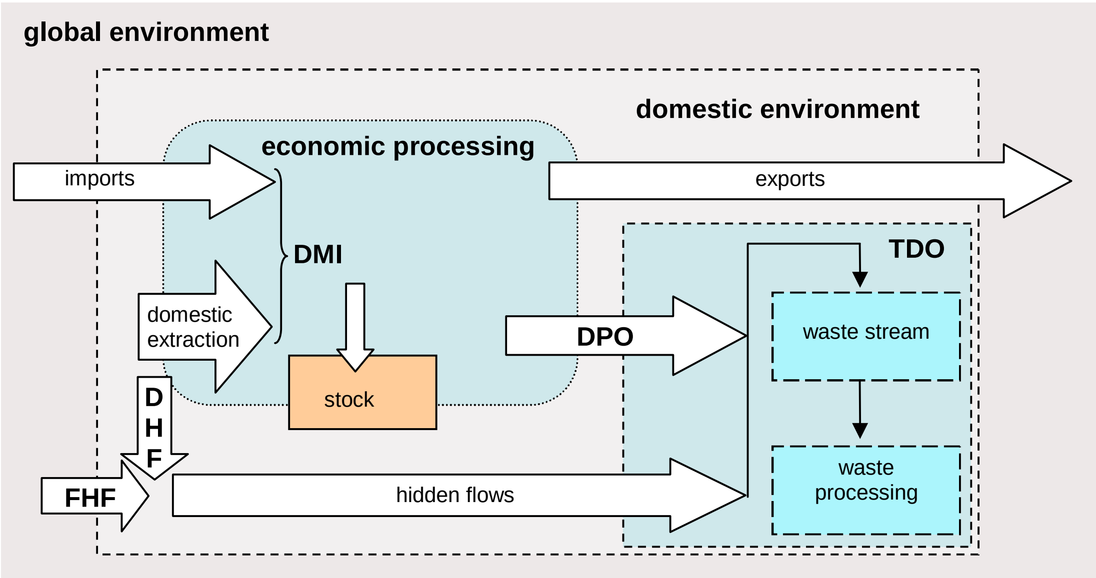

Table 1. Values for the base model variables (adapted from [19], [25], [26])

| variable | deemed value | definition |
|---|---|---|
| $Q_i$ | 33% | Proportion of DMI imported from abroad |
| $Q_{de}$ | 67% | Proportion of DMI extracted domestically |
| $Q_{fhf}$ | 2 | Mass (t) of hidden flows per tonne of imported material |
| $Q_{dhf}$ | 0.6 | Mass (t) of hidden flows per tonne of domestically extracted material |
| $Q_{nas}$ | 65% | Proportion of DMI becoming a net addition to stock [26] |
| $Q_e$ | 8% | Proportion of DMI exported as output |
| $Q_{dpo}$ | 27% | Proportion of DMI existing economic processing as wastes and emissions [26] |
| DMI | 1508 Mt | Baseline domestic material input |

Table 2. Variables adopted for the technologically advanced future scenario

| variable | time interval | | | reference |
|---|---|---|---|---|
| | T1 | T2 | T3 | |
| $Q_{nas}$ | 68.9% | 73.0% | 77.4% | |
| $Q_{dpo}$ | 23.0% | 18.7% | 14.1% | |
| $Q_e$ | 8.1% | 8.3% | 8.5% | |
| $Q_{de}$ | 75.2% | 81.4% | 86.1% | |
| $Q_i$ | 24.8% | 18.6% | 13.9% | |
| $Q_{dhf}$ | 0.51 | 0.43 | 0.37 | |
| DMI (Mt) | 1900 | 2200 | 2400 | |
| landfill | 15% ($^{w}/_{w}$) reduction for each waste each time period | | | All figures adapted from [25], [26], [34] and [37]. Figures have been exaggerated to highlight the changes in the model calculation |
| recycling | 50% ($^{w}/_{w}$) of reduced amount added each time period | | | |
| energy recovery | 25% ($^{w}/_{w}$) of reduced amount added each time period | | | |
| other recovery | 25% ($^{w}/_{w}$) of reduced amount added each time period | | | |
| other disposal | 15% ($^{w}/_{w}$) reduction for each waste each time period | | | |

Table 3. Results for the baseline scenario

| Variable | total mass (Mt) (Sum T1-T3) |
|---|---|
| imports | 1493 |
| domestic extraction | 3031 |
| FHF | 2986 |
| DHF | 1819 |
| exports | 362 |
| DPO | 1222 |
| TDO | 6026 |
| NAS | 2941 |
| | |
| Landfill | 1647 |
| Energy recovery | 85 |
| Recycled | 1819 |
| Other recovery | 143 |
| Other disposal | 2336 |

Table 4. Sensitivity analysis of the baseline scenario to parameter changes

| parameter varied from baseline set (Table 1) | variable | initial mass (Mt) | mass following parameter change (Mt) | variance (Mt) |
|---|---|---|---|---|
| Imports; varied from an initial value of 33.0% to 36.5% | imports | 497 | 547 | + 50 |
| | dom. extraction | 1010 | 960 | - 50 |
| | FHF | 995 | 1090 | + 95 |
| | DHF | 606 | 549 | - 30 |
| | NAS | 980 | 980 | 0 |
| | Exp | 120 | 120 | 0 |
| | DPO | 407 | 407 | 0 |
| | TDO | 2000 | 2070 | + 70 |
| | Total variance (mt) (positive and negative) | | | 295 |
| Domestic extraction varied from an initial value of 67.0% to 73.7% | imports | 497 | 396 | - 101 |
| | dom. extraction | 1010 | 1110 | + 100 |
| | FHF | 995 | 793 | - 202 |
| | DHF | 606 | 666 | + 60 |
| | NAS | 980 | 980 | 0 |
| | Exp | 120 | 120 | 0 |
| | DPO | 407 | 407 | 0 |
| | TDO | 2000 | 1867 | - 133 |
| | Total variance (mt) (positive and negative) | | | 596 |
| DHF; varied from an initial value 0.6 tonne/tonne to 0.66 tonne/tonne | imports | 497 | 497 | 0 |
| | dom. extraction | 1010 | 1010 | 0 |
| | FHF | 995 | 995 | 0 |
| | DHF | 606 | 666 | + 60 |
| | NAS | 980 | 980 | 0 |
| | Exp | 120 | 120 | 0 |
| | DPO | 407 | 407 | 0 |
| | TDO | 2000 | 2060 | + 60 |
| | Total variance (mt) (positive and negative) | | | 120 |
| FHF; varied from an initial value of 2 tonne/tonne to 2.2 tonne/tonne | imports | 497 | 547 | 0 |
| | dom. extraction | 1010 | 960 | 0 |
| | FHF | 995 | 1090 | + 95 |
| | DHF | 606 | 606 | 0 |
| | NAS | 980 | 980 | 0 |
| | Exp | 120 | 120 | 0 |
| | DPO | 407 | 407 | 0 |
| | TDO | 2000 | 2100 | + 100 |
| | Total variance (mt) (positive and negative) | | | 195 |
| Exports; varied from an initial value of 8% to 8.8% | imports | 497 | 497 | 0 |
| | dom. extraction | 1010 | 1010 | 0 |
| | FHF | 995 | 995 | 0 |
| | DHF | 606 | 606 | 0 |
| | NAS | 980 | 980 | 0 |
| | Exp | 120 | 132 | + 12 |
| | DPO | 407 | 395 | - 12 |
| | TDO | 2000 | 1990 | - 10 |
| | Total variance (mt) (positive and negative) | | | 34 |
| NAS; varied from an initial value of 65% to 71.5% | imports | 497 | 497 | 0 |
| | dom. extraction | 1010 | 1010 | 0 |
| | FHF | 995 | 995 | 0 |
| | DHF | 606 | 606 | 0 |
| | NAS | 980 | 1070 | + 90 |
| | Exp | 120 | 120 | 0 |
| | DPO | 407 | 309 | - 98 |
| | TDO | 2000 | 1010 | - 90 |
| | Total variance (mt) (positive and negative) | | | 278 |
| DPO; varied from | imports | 497 | 497 | 0 |

| | | | | |
|---|---|---|---|---|
| an initial value of 27% to 29.7% | dom. extraction | 1010 | 1010 | 0 |
| | FHF | 995 | 995 | 0 |
| | DHF | 606 | 606 | 0 |
| | NAS | 980 | 939 | - 41 |
| | Exp | 120 | 120 | 0 |
| | DPO | 407 | 447 | + 40 |
| | TDO | 2000 | 2040 | + 40 |
| | Total variance (mt) (positive and negative) | | | 121 |
| | imports | 497 | 547 | + 50 |
| | dom. extraction | 1010 | 1110 | + 100 |
| DMI; varied from an initial value of 150 Mt to 1658.8 Mt | FHF | 995 | 1090 | + 95 |
| | DHF | 606 | 666 | + 60 |
| | NAS | 980 | 1070 | + 90 |
| | Exp | 120 | 132 | + 12 |
| | DPO | 407 | 447 | + 40 |
| | TDO | 2000 | 2200 | + 200 |
| | Total variance (mt) (positive and negative) | | | 642 |

Table 5. Scenario analysis, UK runs out of domestic resources

| Variable | T1 (Mt) | T2 (Mt) | T3 (Mt) | total (Mt) | change (Mt) | var. from base scenario (Mt) |
|---|---|---|---|---|---|---|
| imports | 829 | 1030 | 1290 | 3149 | 461 | 1658 |
| dom. extraction | 678 | 500 | 211 | 1389 | -467 | -1641 |
| FHF | 1650 | 2070 | 2590 | 6310 | 940 | 3325 |
| DHF | 407 | 282 | 126 | 815 | -281 | -1003 |
| TDO | 2464 | 2759 | 3123 | 8346 | 659 | 2346 |

Table 6. Scenario analysis, a technically advanced future

| Variable | T1 (Mt) | T2 (Mt) | T3 (Mt) | total (Mt) | change (Mt) | var. from base scenario (Mt) |
|---|---|---|---|---|---|---|
| imports | 471 | 409 | 333 | 1213 | -138 | -278 |
| dom. extraction | 1420 | 1790 | 2060 | 5270 | 640 | 2240 |
| FHF | 942 | 818 | 667 | 2427 | -275 | -558 |
| DHF | 728 | 770 | 764 | 2262 | 36 | 444 |
| TDO | 2107 | 1999 | 1769 | 5875 | -338 | -125 |
| exports | 153 | 183 | 204 | 540 | 51 | 180 |
| NAS | 1300 | 1610 | 1860 | 4770 | 560 | 1830 |
| DPO | 437 | 411 | 338 | 1186 | -99 | -35 |
| | | | | | | |
| landfill | 450 | 395 | 299 | 1144 | -152 | -497 |
| recycling | 687 | 737 | 716 | 2141 | 30 | 326 |
| energy recovery | 129 | 167 | 177 | 473 | 49 | 388 |
| other recovery | 102 | 139 | 154 | 396 | 52 | 254 |
| other disposal | 667 | 559 | 421 | 1646 | -246 | -679 |