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Research article

Development of a system model to predict flows and performance of regional waste management planning: A case study of England

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ABSTRACT

Significant loss of valuable resources and increasing burdens on landfills are often associated with a lack of proper planning in waste management and resource recovery strategy. A sustainable waste management model is thus urgently needed to improve resource efficiency and divert more waste from landfills. This paper proposes a comprehensive system model using stock-and-flow diagram to examine the current waste management performance and project the future waste generation, treatment and disposal scenarios, using England as a case study. The model comprises three integrated modules to represent household waste generation and collection; waste treatment and disposal; and energy recovery. A detailed mass and energy balance has been established and waste management performance has been evaluated using six upstream and downstream indicators. The base case scenario that assumes constant waste composition shows that waste to landfills can be reduced to less than 10% of the total amount, by 2035. However, it entails greater diversion of waste to energy-from-waste facilities, which is not sustainable and would incur higher capital investment and gate fees. Alternative case scenarios that promote recycling instead of energy recovery result in lower capital investment and gate fees. Complete elimination of the food and organic fraction from the residual waste stream will help meet the 65% recycling target by 2035. In light of the need for achieving a more circular economy in England, enhancing material recovery through reuse and recycling, reducing reliance on energy-from-waste and deploying more advanced waste valorisation technologies should be considered in future policy and planning for waste management.

1. Introduction

Excessive exploitation of resources due to increasing population and demand, inefficient waste management planning and resource recovery strategy and the lack of public awareness and participation have resulted in significant loss of valuable resources, increased burdens on landfills and other environmental pollution. Promoting resource efficiency through reuse and recycling and diverting waste from landfills are the two key priorities in the waste management policies in the UK (DEFRA, 2021a; HM Government, 2018a, 2018b). Waste management is a complex problem and needs to be addressed using a systems approach (Ng et al., 2019; Ng and To, 2020). Systems approach has been applied in various contexts for policy making such as waste management (Ng et al., 2019), agriculture and natural resource management (Bosch et al., 2007), business and organisational management (Senge, 1990; Sterman, 2000). Systems thinking has also been adopted to understand the overall impact of certain activities or events on the economic, environmental or social systems through analysis of the interconnectedness of different elements, as demonstrated in recent studies to understand the impact of Ukraine-Russia war on food and biofuel markets (Shams Esfandabadi et al., 2022), and the environmental impact of carsharing services (Shams Esfandabadi et al., 2020).

Transforming the existing waste management model to a more sustainable model requires a holistic view on the system that includes the elements and interconnections on both the upstream waste generation and collection, as well as downstream treatment and disposal. The complex behaviour of a system can be examined using system dynamics, a computational modelling method for systems thinking developed by Forrester (1958) that enables us to explore interaction among different elements or factors in a system. This method is very effective in

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predicting waste generation based on limited data (Dyson and Chang, 2005; Kollikkathara et al., 2010; Pinha and Sagawa, 2020) and has been applied in exploring management strategies for specific waste streams such as source-segregated food and biodegradable fractions of municipal solid waste in Hong Kong (China) (Lee et al., 2019) and Oita City (Japan) (Babalola, 2019); construction and demolition waste in Hong Kong (China) (Mak et al., 2019); and waste electrical and electronic equipment (WEEE) in China (Guo et al., 2018). Detailed mass and energy balances that incorporate the efficiency of treatment technologies to account for main product generation, emissions and losses are not considered adequately in these models. Such limitations often lead to inaccurate prediction of the actual resources that can be recovered, the economic cost and benefits as well as the associated environmental impact due to emissions and unintentional loss to the environment. Furthermore, it can be seen that these system dynamics models are location specific, which are highly dependent on the waste characteristic, behaviour of citizen and waste management infrastructure and policies in those regions. Also, the attributes and model formulation are dependent upon the specific purpose and boundary (e.g. time/period and geographic location) of the study. This implies that the models cannot be directly adopted for any other purposes or case studies as this may lead to flawed conclusions.

The deployment of system dynamics to inform policy making in waste management context has been demonstrated in previous region-specific case studies, which can be categorised into upstream (waste generation); downstream (waste treatment and disposal); and hybrid upstream and downstream models. For upstream modelling, Dyson and Chang (2005) developed dynamic simulation models to forecast solid waste generation in San Antonio, Texas (USA) in view of obtaining a better estimation for the capacity of material recovery facilities (MRF) in that region. This work has considered different factors such as population, household income, people per household, total income per service centre and historical amount generated. Another recent study conducted by Sukholthaman and Sharp (2016) explored the effect of source separation on waste collection in Bangkok (Thailand). For downstream modelling, Ulli-Beer et al. (2007) investigated the effect of different pricing and incentive strategies on human behaviour and budget goals using a system dynamics approach, in view of promoting household recycling practices in Switzerland. Sustainable waste management based on principles of waste hierarchy (prevention, reuse, recycling, recovery and disposal) through separate collection and treatment methods were not widely practised in the past and hence earlier studies have not considered the options of processing different waste streams. Sufian and Bala (2006) attempted to estimate the electricity generation potential and total electricity demand from solid waste in Dhaka (Bangladesh) by correlating solid waste generation to population. Recent studies (Kollikkathara et al., 2010; Pinha and Sagawa, 2020; Inghels and Dullaert, 2011) have considered more comprehensive hybrid models for examining the generation of separately collected waste streams and the associated treatment options. Kollikkathara et al. (2010) examined the impact of waste prevention decision options using a dynamic simulation model on the municipal solid waste (MSW) generation rate, remaining landfill capacity, and economic cost or benefit by considering different waste processing options in Newark city (USA). The model adopted the same principles and structure as in the LCA-IWM waste prognosis tool (den Boer et al., 2007), with inclusion of an additional landfill capacity estimation module and considered the socio-economic and demographic factors (i.e. population density, gross domestic product (GDP), life expectancy at birth, infant mortality rate and labour force) to forecast the rate of waste generation. Inghels and Dullaert (2011) developed a system dynamics model by exploiting the relationships between GDP, population and selective collection behaviour, and examined the effectiveness of policy measures for Flemish household waste management including collection, reuse, recycling and disposal. Pinha and Sagawa (2020) developed a system dynamics model to represent the MSW management scenario in Araraquara (Brazil) for financial planning purposes, consisting of waste generation and destinations, recycling streams, revenues and expenditures modules. Sustain Ltd. has developed two system dynamics models for the UK Department for Environment, Food and Rural Affairs (DEFRA), i.e. plastic packaging recycling and waste prevention models to support policy making in these areas (Freeman et al., 2014). Although these models have been developed to a level of details which can be adopted to examine the effectiveness of policy interventions (subject to further calibration, testing and validation), the applications are still limited to specific waste streams. Residual waste (or general waste) stream contains significant amount of materials that are potentially recoverable or recyclable, but often being overlooked in existing studies. It is crucial to consider all waste streams collectively when conducting preliminary assessments so that a more reliable prediction of waste management performance and resource recovery potential at a regional or country level can be obtained. Looking at specific waste streams without a holistic assessment on the overall waste management system may lead to environmental burden shifting when improvement is made on a specific area and may undermine the full potential of resource recovery.

In this study, England has been selected as the case study because it represents more than 80% of household waste arisings in the UK (DEFRA, 2020a). A comprehensive system model with detailed mass and energy balances for the waste management system in England is currently lacking and this has hindered the progress of transformation and has limited the opportunities to improve resource recovery. It is crucial that the model incorporates the efficiency of treatment technologies to account for product generation, emissions and losses to obtain a better estimate of the resources that can be recovered, the economic cost and benefits as well as the associated environmental impact due to emissions and unintentional loss to the environment.

The novelty of this research lies in developing a holistic and comprehensive system model with validated mass and energy balances to analyse waste management scenarios in England. The model enables the variation of waste generation as a function of population to be captured at the upstream collection, and also enables full exploration of the impact on the whole waste management system through the interconnection with downstream treatment, recovery and disposal processes. Household waste is the main focus of this study because it consists of a mixture of heterogeneous resources which can potentially be recovered if proper separation, collection and treatment methods are implemented. The model considers all the segregated recyclable and residual waste streams as well as representative technologies for treatment of individual waste streams. This model has been developed in Vensim (Ventana Systems, 2015) to enable future development of a more sophisticated system dynamics model, with the inclusion of socio-economic and environmental variables and potential feedback loops that are relevant for policy-making. The objectives of this study are to (a) establish a comprehensive system model with validated mass and energy balances to predict future household waste generation and treatment scenarios; (b) test the model using waste management data in England as a case study and provide recommendations based on scenario analysis to inform future direction for policy interventions.

2. Methodology

The methodology outlined in Fig. 1 has been adopted in this study to model the waste management scenarios.

1. Problem Definition: Policy review was conducted to understand the current policies, strategies and goals/targets related to waste management at national (England) level. This was followed by defining purpose of study where the aim of the study and intended users of the model were identified and research questions were formulated. Lastly, boundary of study such as geographic location and time/period boundary was defined.

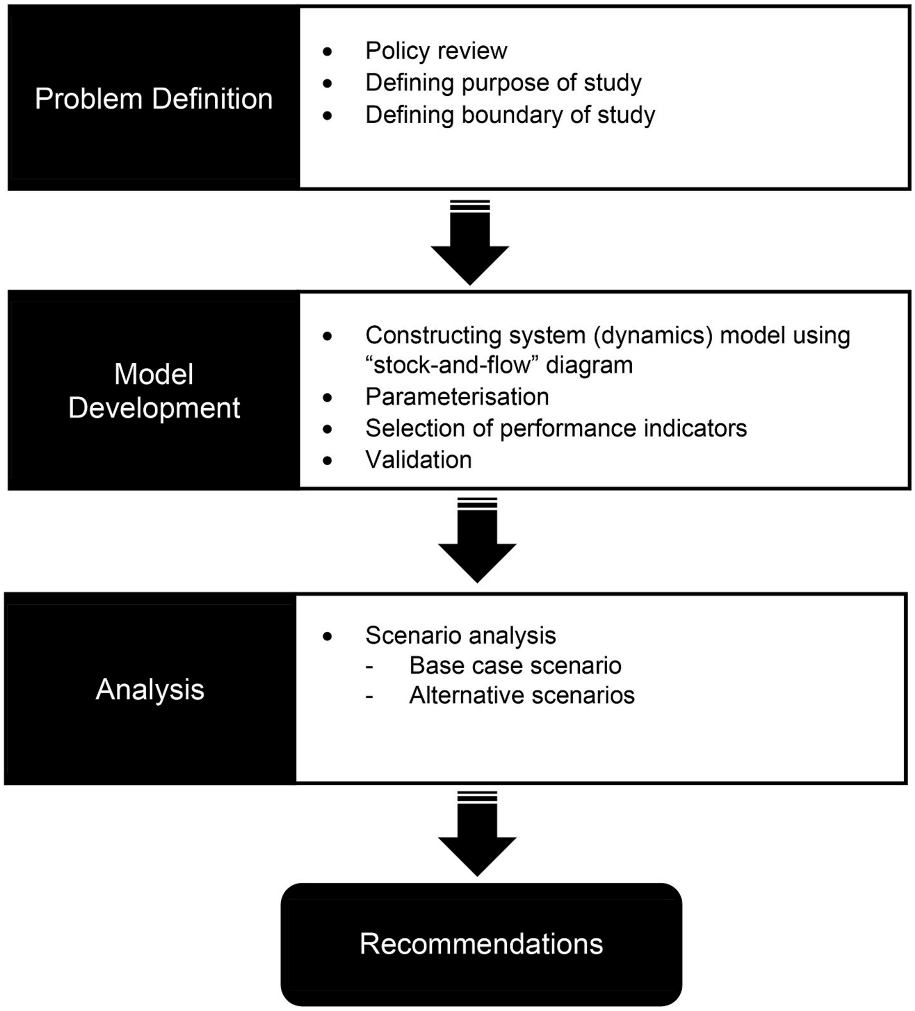


Fig. 1. Systems approach for modelling waste management system.

2. Model Development: The waste management system was structured into three integrated modules according to their functionalities, i.e. waste generation and collection, waste treatment and disposal, and energy recovery. The stock-and-flow diagram was developed in Vensim® PLE Plus 8.2.1 environment. The model was developed based on information obtained from literature or derived using a regression method, and was validated against literature. In the present context, only population and landfill are modelled as "stocks" as they carry significance towards the waste generation and impact on the environment. The upstream performance of waste management system was evaluated using the relevant indicators (refer to section 3.2.2) selected from the *Resources and Waste Strategy* (HM Government, 2018b), based on the reported amount of household waste generated. On the other hand, downstream performance indicators have been proposed in the present study to quantify the materials that are processed through treatment facilities (i.e. recycling and recovery) and residual waste that is disposed of to landfill, estimated using the results generated from the model. The simulated results using Vensim were validated against the 2015 and 2019 data presented by DEFRA (2021b). The amount of household waste generation and composition, amount of waste to treatment and disposal and performance indicators were compared.

3. Analysis: A base case scenario was developed by assuming constant waste composition, i.e. the fraction of separate collected household waste stream does not change over time. Alternative scenarios were explored to understand the impact of increasing recycling rate by assuming certain waste components from residual waste stream were recycled. These scenarios were compared to examine whether the policy target can be met within the designated timeframe and the economic implications.

4. Recommendations: Strategic recommendations were generated based on the scenario analysis to provide future direction of policy making in waste management.

Sources of data: The data for household waste generation (total and segregated waste streams), amount of waste sent for recycling, EfW and landfills, were obtained from *WasteDataFlow* database (www.wastedataflow.org) or DEFRA's publication (DEFRA, 2021b). For detailed household residual waste composition, the relevant data were found in WRAP's publication (WRAP, 2020). The data for population in England was obtained from the Office for National Statistics (ONS) publication (ONS, 2020).

3. Modelling waste management scenarios in england

3.1. Problem definition

Policy review: The UK was required to meet a minimum EU household waste recycling target of 50%, however the most recent data in 2018 (published in March 2020) indicated that the recycling rate has reached a plateau at around 45% in recent years (DEFRA, 2020a). Wales is the only nation in the UK that has achieved 54%, while England, Scotland Northern Ireland have reached 43–48%. The EU and UK have further committed to achieve more ambitious targets for municipal waste (i.e. household waste and commercial waste with similar composition to household waste) management where a recycling rate of at least 65% and reduction of municipal waste to landfill to 10% or lower must be met by 2035 as outlined in the *Resource & Waste Strategy for England* (HM Government, 2018b) and *Waste Management Plan in England* (DEFRA, 2021a), transposed from the *EU Circular Economy Package* (European Commission, 2015, 2018). It is imperative to reduce the amount of waste to landfill to lower the emissions of GHG as laid out in the *EU Landfill Directive* (European Commission, 1999). The forthcoming Environment Bill, a legislation framework that may come into force by 2023, will further introduce measures to promote consistent recycling collections and regular separate food waste and garden waste collections (DEFRA, 2020b).

Purpose of the study: This study aims to establish a comprehensive system model that is capable of predicting waste generation from household based on population and household waste generation per capita; amount of waste materials that can be recycled and recovered; products, rejected materials, emissions/discharge/losses generated from waste treatment facilities; and the amount of waste sent to landfills. The model employed data from literature to establish the mass and energy balances of the waste management system, which is useful for analysing the efficiency of recycling and rate of landfilling. This model is used to answer the research question: *What will be the economic implications of increasing recycling rate and diverting waste from landfills on waste management planning?*

This study includes key performance indicators such as recycling rate, resource recovery potential and waste diversion from landfill to recycling that are relevant for policy making in terms of measuring the progress of target achievement. Economic, environmental and social indicators are beyond the scope of this study. The intended users for this model and analysis are policy makers at both national and local authority levels in England, researchers and waste planning managers.

Boundary of study: This study considers the household waste management system in England for a time horizon of 20 years (2015–2035). The model has taken 2015 as the base year (Year 0) since the local authorities in England (and throughout the UK) have adopted the revised Question 100 (Q100) waste data reporting methodology and structure (which enabled reporting of waste that goes through various treatment processes, e.g. including outputs from incineration) starting from 2015 (DEFRA, 2020a). Fig. 2 illustrates the current waste management in England including household waste generation, treatment and disposal to landfill. Household waste is constituted by a mixture of heterogeneous resources and can be separated at source into different waste streams based on treatment methods. In England, household waste can be separated into four main streams: dry recyclables, organic (garden) waste, food waste and residual waste. These segregated waste streams are collected and transported using refuse collection trucks to the respective treatment facilities. Dry recyclables mainly consist of

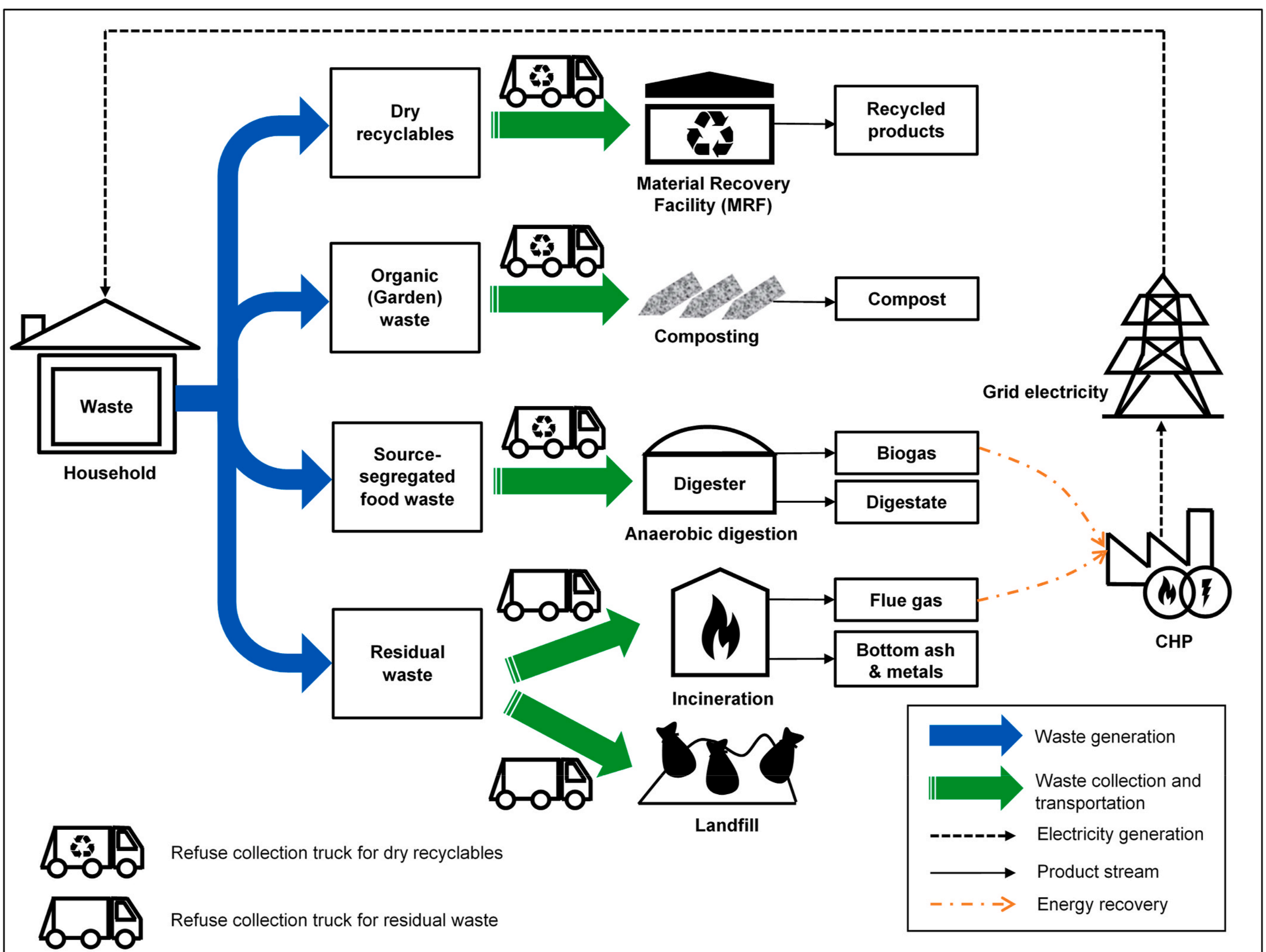


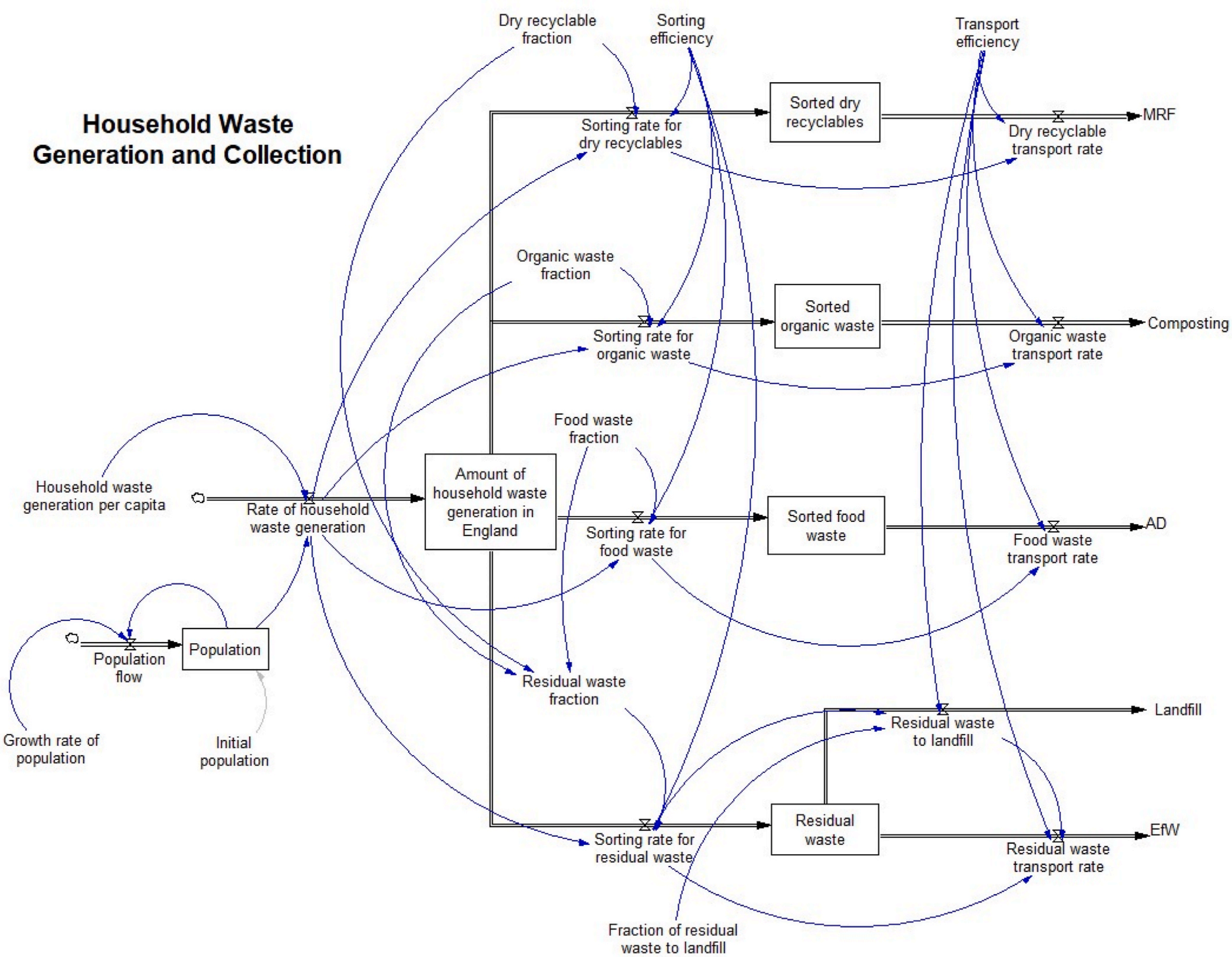
Fig. 2. Concept mapping of waste management model in England.

paper/card, glass, metals and plastics. These materials are recycled through material recovery facilities (MRF) and the products are sold to secondary market. Food and garden wastes are wet biodegradable wastes (or bio-wastes) and should in principle be diverted from landfills. The most common methods of treating these biowastes are using composting and anaerobic digestion (AD) (HM Government, 2018a). In the present context, composting is used for treating garden waste while AD is used for treating source-segregated food waste. Composting is a decomposition process of organic matters under aerobic (i.e. oxygen requiring) conditions together with the presence of naturally-occurring microorganisms. A stabilised product known as “compost” that can be used as soil improver is generated. AD is a decomposition process of organic matters under anaerobic (i.e. absence or limited oxygen) conditions with the presence of microorganisms. AD converts organic matters into biogas that contains mainly methane and carbon dioxide, and digestate that can be used as fertiliser. Biogas produced from AD can be fed into combined heat and power (CHP) to generate heat and electricity. The UK government is promoting the use of AD as the preferred method for food waste treatment and the technology has demonstrated clear environmental benefits, as indicated in the *Anaerobic Digestion Strategy and Action Plan* (DECC and DEFRA, 2011; House of Commons, 2017). Any wastes that are not properly segregated or not suitable for reuse and recycling are considered as residual waste and are sent to either energy-from-waste (EfW) facilities or directly to landfills. EfW in England normally refers to incineration with energy recovery facilities. This modelling study has assumed that CHP is installed within the EfW facilities. Electricity generated from both EfW and AD can be exported to the grid and supplied to household within local community. Heat can also be exported if heating network is available. Although some of the technologies might not be readily available at the current state in certain areas in England, the aforementioned treatment pathways for different waste streams are considered to be the most likely scenario within the timeframe of 20 years. Alternative technologies such as mechanical-biological treatment (MBT), gasification and pyrolysis which are not widely adopted in England are not considered. Waste transfer station, a temporary storage of municipal waste before it is transferred to other facilities, is not included in this study.

3.2. Model development

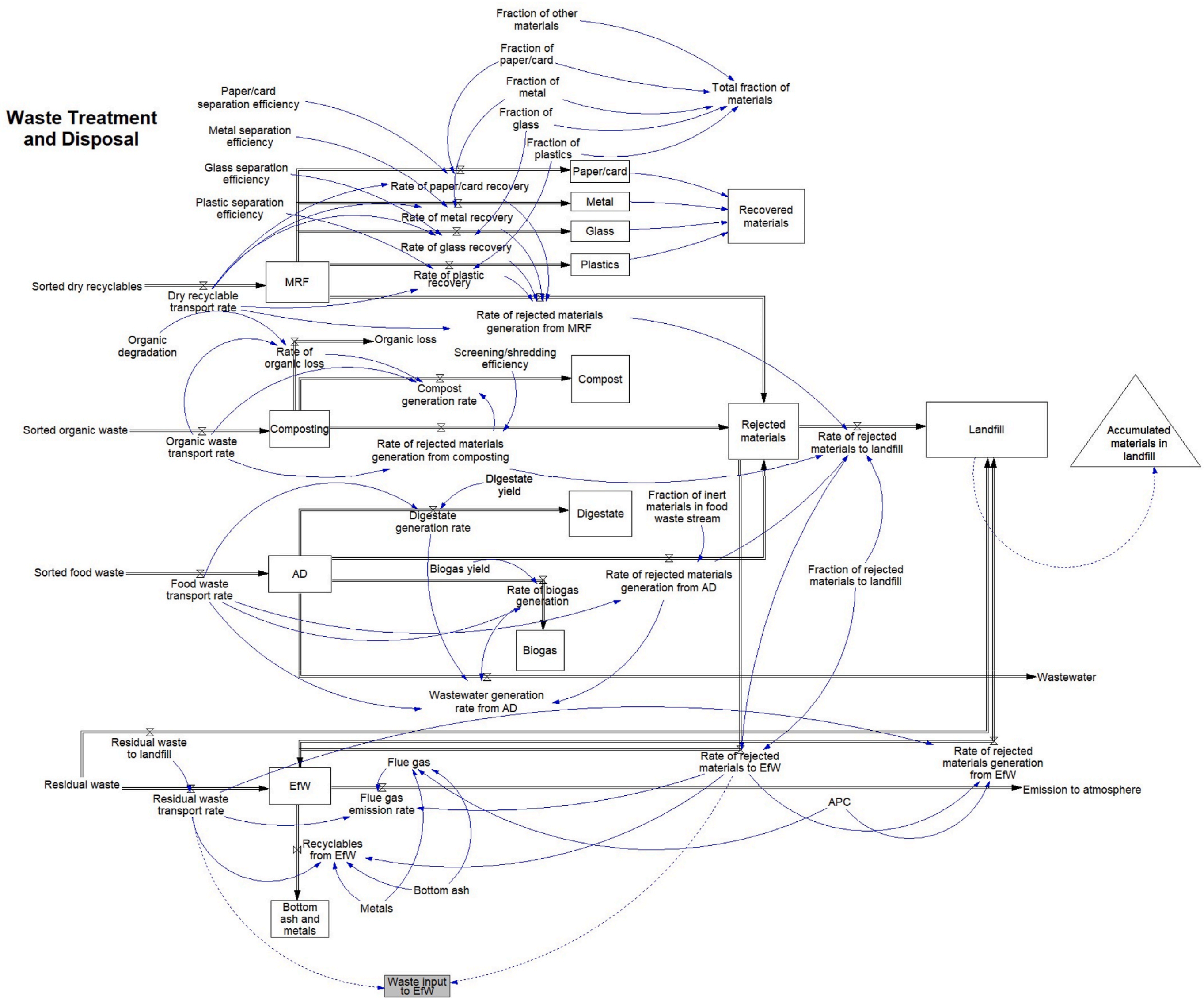
3.2.1. Stock-and-flow diagram and parameterisation

A stock-and-flow diagram of the waste management system has been structured into three integrated modules: (i) Household Waste Generation and Collection (Fig. 3(a)); (ii) Waste Treatment and Disposal (Fig. 3



(a)

Fig. 3. Vensim model showing (a) Household Waste Generation and Collection module; (b) Waste Treatment and Disposal module; and (c) Energy Recovery module.



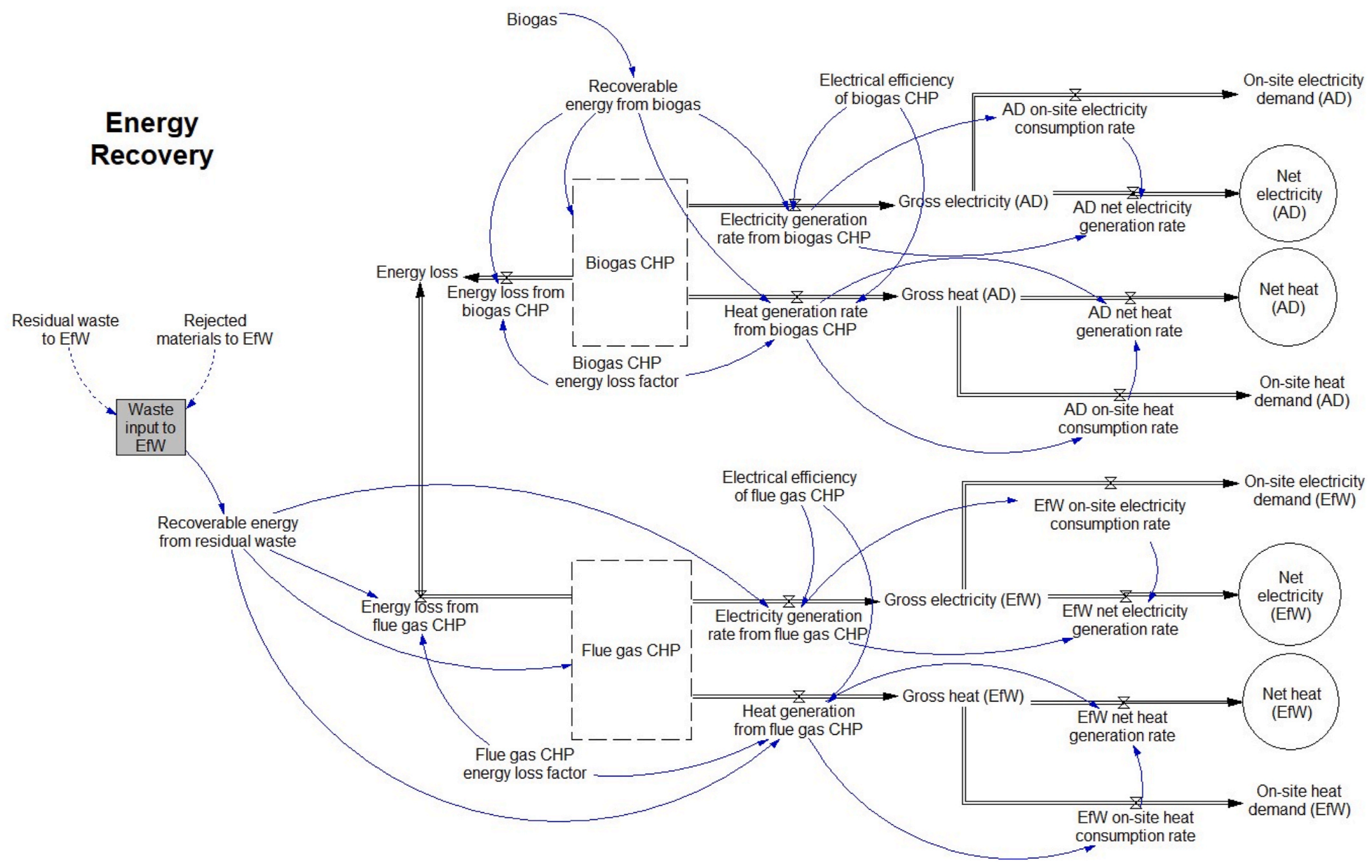
(b)

Fig. 3. (*continued*).

(b)); and (iii) Energy Recovery modules (Fig. 3(c)). These diagrams are interconnected. The output streams from Fig. 3(a) (i.e. MRF, Composting, AD, Landfill and EFW) are connected to the input streams in Fig. 3(b). A fraction of residual waste from household and rejected materials are considered as "waste input to EfW" in Fig. 3(b) and are linked to the Energy Recovery Module in Fig. 3(c). Details of the three modules including the assumptions and input parameters are provided in the Supplementary Materials, Appendix A. The equations used in Vensim model can be found in Appendix B.

3.2.2. Selection of performance indicators

Both upstream and downstream performance indicators were used in the evaluation of waste management system in this study, presented in Table 1. Upstream performance indicators comprise (U1) recycling rate that either includes or excludes incineration bottom ash (IBA) metals; (U2) percentage of household waste landfilled; and (U3) percentage of household waste sent to EfW. Downstream performance indicators include (D1) resource recovery potential; (D2) percentage of materials landfilled; and (D3) waste diversion from landfill to recycling. These performances were calculated using Equations (1)-(6) shown in Table 1. These indicators cover the three key policy priority areas, i.e. reducing waste generation, increase recycling and reducing landfilling which are essential in monitoring progress in waste minimisation (Goal 8 in the 25 Year Environmental Plan (HM Government, 2018a)) as set out in the Resources and Waste Strategy (HM Government, 2018b) (Note: the full indicator framework can be found in the Supplementary Materials, Table A.5). The Department for Communities and Local Government (currently the Ministry of Housing, Communities and Local Government (MHCLG)) has published the National Indicators for Local Authorities and Local Authority Partnerships: Handbook of Definitions (Communities and Local Government and HM Government, 2008) in 2008, introducing 198 national indicators of which 3 of them are relevant to waste management: residual household waste per household (NI 191); percentage of household waste sent for reuse, recycling and composting (NI 192); and percentage of municipal waste landfilled (NI 193). The indicators adopted in the present study, U1, U2, U3 and D2 are consistent with the national indicators adopted by local authorities and DEFRA, and are included in WasteDataFlow reporting. The indicators D1 and D3, proposed in the present study, go beyond the DEFRA and local authorities' deployed metrics and are highly relevant to measuring the performance of the waste management system in England and the UK. Resource recovery potential (D1) considers the amount of materials



(c)

Fig. 3. (*continued*).

(i.e. recovered products from MRF, compost, digestate and biogas from AD, and IBA metals and bottom ash from EfW) that can potentially be recovered via downstream treatment processes, represented by percentage with respect to total household waste, as opposed to recycling rate (U1) that only considers the amount of household waste prepared for recycling. Waste diversion from landfill to recycling (D3) measures the percentage of waste diverted from landfill that goes to recycling instead of energy recovery, as opposed to percentage of household waste/materials landfilled (U2/D2) that only considers the waste that goes to landfill. D3 considers total household waste but eliminates emissions (e.g. wastewater discharge and flue gas to atmosphere) and losses (e.g. organic loss in composting due to degradation) to give the net efficiency of waste diversion from landfill to recycling. In addition to the six indicators discussed above, this study has also included the amount of waste generation, recovered products, emissions/discharge/losses and recovered energy (electricity and heat) in the mass and energy balances of the waste management system.

4. Results and discussion

4.1. Model validation

Results generated using the Vensim model developed in section 3.2.1 were compared against DEFRA's data (DEFRA, 2021b) in 2015 and 2019 based on waste generation, waste destination (recycling, landfill and EfW), presented in Table 2. The simulated results are in reasonably good agreement with DEFRA's data with ±0.1–4.3% discrepancy (except for the amount of food waste generation). Although the percentage discrepancy seems relatively high for the amount of food waste generation, the absolute discrepancy (i.e. 0.06) is small and thus this is acceptable.

4.2. Scenario analysis

A base case scenario and two alternative case scenarios were examined by adopting the system model for the waste management system in England, developed in Vensim. The base case scenario presented in section 4.2.1 assumed constant composition of household waste stream and hence the recycling rate (excluding IBA metals) remains unchanged from 2015 to 2035. This assumption is particularly valid in 2015–2019 based on the actual data where the compositions have reached a plateau (DEFRA, 2021b). Alternative scenarios considered certain fraction of waste components in the household residual waste stream were diverted to recycling streams (i.e. dry recyclables, segregated food waste and organic/garden waste). Scenario 1 assumed that all paper/card, metals, glass and plastics embedded in the household residual waste stream were shifted to dry recyclable stream, while Scenario 2 assumed that food and garden wastes in the household residual waste stream were recycled, by 2035, presented in section 4.2.2. The composition of waste component in the household residual waste stream can be found in the Supplementary Materials, Table A.6. The composition of household waste stream in the base case and alternative case scenarios and the targeted recycling rate in 2035 are presented in Table A.7. The economic implications on the treatment facilities and local authorities of these scenarios are analysed in section 4.3.

4.2.1. Base case scenario

The base case scenario assumed constant dry recyclables, organic

Table 1
Performance indicators for waste management system.

Indicator		Description	Equation	
Upstream				
U1	Recycling rate (Method 3)	The calculation for recycling rate in the UK follows calculation method 3 "preparation for reuse and recycling of household waste" in accordance to the Waste Framework Directive Commission Decision 2011/753/EU (European Commission, 2011). Metal recovered from IBA has been included in the "recycling" category since 2018 (DEFRA, 2020a).	$\text{Recycling rate of household waste (\%)} = \frac{\text{Recycled amount of household waste}}{\text{Total household waste excluding certain waste categories}^{(i)}} \times 100$	(1)
U2	Percentage of household waste landfilled	This indicator (similar to DEFRA's definition for "percentage of municipal waste[ii] landfilled" (Local Government Association, 2021)) accounts for the residual waste from household sent directly to landfill.	$\text{Percentage of household waste landfilled (\%)} = \frac{\text{Residual waste from household waste sent directly to landfill}}{\text{Total household waste excluding certain waste categories}^{(i)}} \times 100$	(2)
U3	Percentage of household waste sent to EfW	This indicator accounts for residual waste from household sent directly to EfW.	$\text{Percentage of household waste sent to EfW (\%)} = \frac{\text{Residual waste from household waste sent to EfW}}{\text{Total household waste excluding certain waste categories}^{(i)}} \times 100$	(3)
Downstream				
D1	Resource recovery potential	This indicator considers the final recovered materials from household waste, including: •recovered materials such as paper/card, glass, metals and plastics from MRF; •compost; •digestate and biogas from AD; •IBA metals and bottom ash. Energy products such as heat and electricity are not considered as recovered materials in this calculation.	$\text{Resource recovery potential of household waste (\%)} = \frac{\text{Final recovered materials from household waste excluding energy product}}{\text{Total household waste excluding certain waste categories}^{(i)}} \times 100$	(4)
D2	Percentage of materials landfilled	This indicator (equivalent to DEFRA's definition for "percentage of municipal waste[ii] landfilled" (Local Government Association, 2021)) accounts for the residual waste from household sent directly to landfill and also the rejected materials from various treatment facilities sent to landfill.	$\text{Percentage of materials landfilled (\%)} = \frac{\text{Residual waste from household including rejected materials sent to landfill}}{\text{Total household waste excluding certain waste categories}^{(i)}} \times 100$	(5)
D3	Waste diversion from landfill to recycling	This indicator considers the final recovered materials from household waste, including: •recovered materials such as paper/card, glass, metals and plastics from MRF; •compost; •digestate and biogas from AD; •IBA metals and bottom ash. Energy products such as heat and electricity are not considered as recovered materials in this calculation. The denominator considers total household waste but eliminates emissions (e.g. wastewater discharge and flue gas to atmosphere) and losses (e.g. organic loss in composting due to degradation).	$\text{Waste diversion from landfill to recycling (\%)} = \frac{\text{Final recovered materials from household waste excluding energy product}}{\text{Total household waste excluding certain waste categories}^{(i)} - \text{Emissions and losses}} \times 100$	(6)

Note.
(i) Waste categories excluded from the calculation of household waste are discarded vehicles, sludges and mineral wastes (European Commission, 2011).
(ii) Municipal waste refers to "household and similar waste" which differs from household waste in this context.

waste, food waste and residual waste fractions of 0.265, 0.168, 0.017 and 0.55, from 2015 to 2035 (see section 3.2.1 and Appendix A in the Supplementary Materials). Fig. 4(a) shows the upstream performance of the waste management in England. The recycling rates stay constant at 45% and 45.7% in the case where IBA metals are excluded and included, respectively. The recycling rate, which is a "collection rate", refers to the fraction of household waste which has been collected and sent for recycling, but does not indicate the actual amount of waste that has been recycled. On the contrary, the resource recovery potential, a downstream indicator shown in Fig. 4(b) has taken into account the amount of waste that has been recycled. The resource recovery potential indicates a minor gradual increase of approximately 10% from 43.8% in 2015 to 48.0% in 2035. The recovered products in 2035 consist of recovered materials from MRF (48%); compost (23%); digestate (1.5%); biogas (0.5%); and IBA metals and bottom ash from EfW (27%). Although the fraction of recovered materials from MRF and compost are among the highest in the total amount of recovered materials, the increment of resource recovery potential is mainly driven by the increase in IBA metals and bottom ash recovered from EfW, by 70% from 2015 to 2035. This is because the fraction of household residual waste to landfill has been projected to decrease exponentially from 4.26 Mt in 2015 to 0.08 Mt in 2035 (according to equation (A.2), see Appendix A and Table A.8 in the Supplementary Materials), and thus more waste is diverted to EfW. The percentage of household waste sent to EfW increases from 35.6% to 54.7% (Fig. 4(a)), while the percentage of household waste (materials) landfilled drops from 19.4% (20.3%) to 0.32% (1.55%) from 2015 to 2035 (Fig. 4 (a) and (b)). Fig. 4(b) also indicates that 96.9% waste diversion from landfill to recycling can be achieved in 2035. Detailed mass balance of the waste management system in England for the base case scenario, generated from Vensim, can be found in the Supplementary Materials, Table A8. Overall, the base case scenario has projected that the recycling rate of 65% (household waste in this context, not municipal waste) cannot be met while it is possible to achieve reduction of waste to landfills to less than 10% of the total amount, by 2035.

Although the national policy documents have not included any energy indicators, this study has considered the potential of energy recovery from waste from 2015 to 2035. The net electricity generation potential from food waste AD and residual waste EfW are 172.8 and 460 kWh/t of waste input, respectively. The net electricity generation from AD and EfW increases from 64.4 GWh to 4057.6 GWh, respectively, in 2015, to 74.2 GWh and 6901.3 GWh, respectively, in 2035. This can

Table 2
Comparison of DEFRA and Vensim's baseline 2015 and 2019 models.

Year		2015			2019		
Parameter	Unit	DEFRA (2021b)	Present study (Vensim)	Discrepancy (± %)	DEFRA (2021b)	Present study (Vensim)	Discrepancy (± %)
Waste generation							
Total household waste generated in England	**Mt**	**22.23**	**21.91**	**1.4**	**22.07**	**22.55**	**2.2**
Residual waste	Mt	12.38	12.05	2.7	11.99	12.40	3.5
Dry recyclables	Mt	5.85	5.81	0.7	5.89	5.98	1.5
Food waste	Mt	0.31	0.37	18.9	0.44	0.38	13.9
Organic waste	Mt	3.71	3.68	0.9	3.75	3.79	1.0
Waste destination							
Household waste recycled	Mt	9.87	9.86	0.1	10.09	10.15	0.6
Household waste to landfill	Mt	4.37 [(i)]	4.26	2.4	1.87 [(i)]	1.92	2.5
Household waste to EfW	Mt	7.88 [(ii)]	7.79	1.1	10.04 [(ii)]	10.48	4.3
Performance indicator							
Recycling rate for household waste (exc. IBA metals)	%	44.40	45.00	1.4	45.70	45.01	1.5
Percentage of household waste landfilled	%	19.65	19.44	1.0	8.48	8.51	0.4
Percentage of household waste sent to EfW	%	35.44	35.55	0.3	45.50	46.47	2.1

[(i)] This was estimated using local authority collected waste of which 19.65% (2015)/8.48% (2019) of the household waste was landfilled.
[(ii)] This was estimated using local authority collected waste of which 35.44% (2015)/45.5% (2019) of the household waste was sent to EfW. This excluded rejected materials from various treatment sites to EfW.

potentially supply 1.4 and 2.4 million households (assuming a medium typical domestic consumption values 2900 kWh per household (Ofgem, 2020)) in 2015 and 2035, respectively. The heat generation can potentially supply for household heating however the heating network is not widely available in England. Detailed energy balance can be found in the Supplementary Materials, Table A.9.

4.2.2. Alternative case scenarios

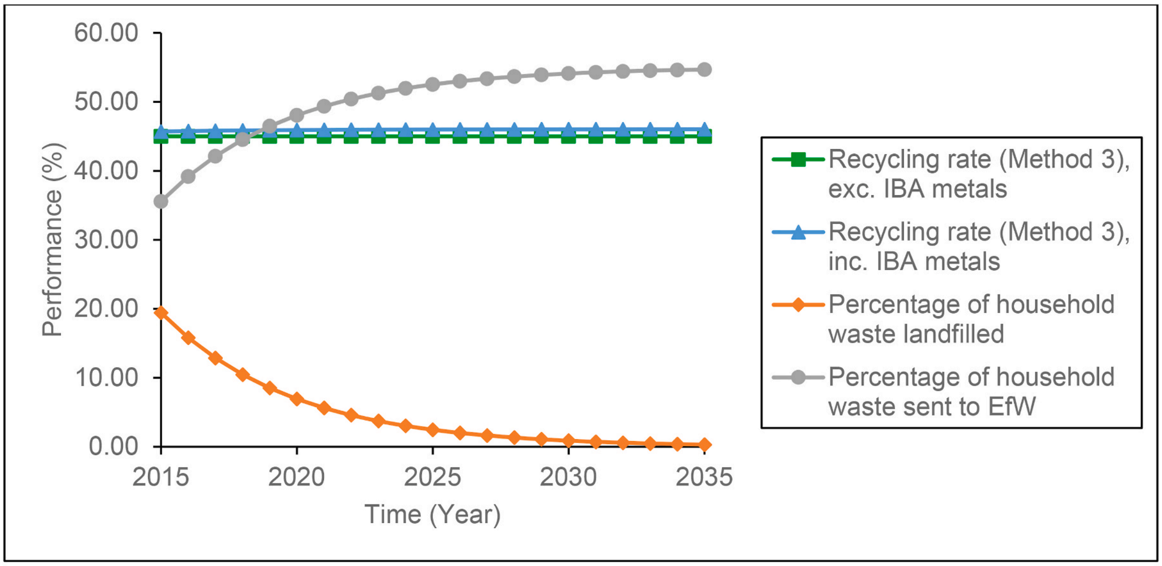
Linear relationship was assumed for the changes of waste composition from the present year 2021–2035. The equations used for forecasting the compositional changes in scenarios 1 and 2 were obtained using linear regression shown in the Supplementary Materials, Table A.10. The alternative scenarios 1 (increased dry recyclable fraction) and 2 (increased food and organic waste fraction) were compared against the base case scenarios based on the recycling rate (exc. IBA metals) (Fig. 5(a)), resource recovery potential (Fig. 5(b)), net electricity generation from AD (Fig. 5(c)) and EfW (Fig. 5(d)).

Fig. 5(a) shows that the recycling rate in scenario 2 (65.8%) is higher than scenario 1 (62.0%) by 2035 since the composition of food and organic waste fraction (37.5%) in residual waste stream is higher than the recyclable materials (30.9%) (see Table A6 in the Supplementary Materials). If the compositions of waste components in residual waste stream in scenario 2 are the same as in the base case, complete elimination of the food and organic fraction from the residual waste stream will help meet the 65% target by 2035. On the contrary, the resource recovery potential in scenario 1 (59.6%) is greater than scenario 2 (55.4%) by 2035 as indicated in Fig. 5(b) due to a higher amount of recycled products recovered from MRF compared to the products from recycling food and organic waste in scenario 1. Fig. 5(c) shows that the net electricity generation from AD in scenario 2 is increased by nearly 11 times by 2035 (808.6 GWh compared to 74.2 GWh in the base case scenario) where more food waste is recycled. The shifting of recyclable materials from residual waste stream to other recycle streams leads to reduction in net electricity generation from EfW, from 6901.3 GWh in the base case scenario to 5193.9 GWh in scenario 1 and 4557.3 GWh in scenario 2, shown in Fig. 5(d). Detailed mass and energy balances for scenarios 1 and 2 are provided in the Supplementary Materials, Tables A.11-A.14.

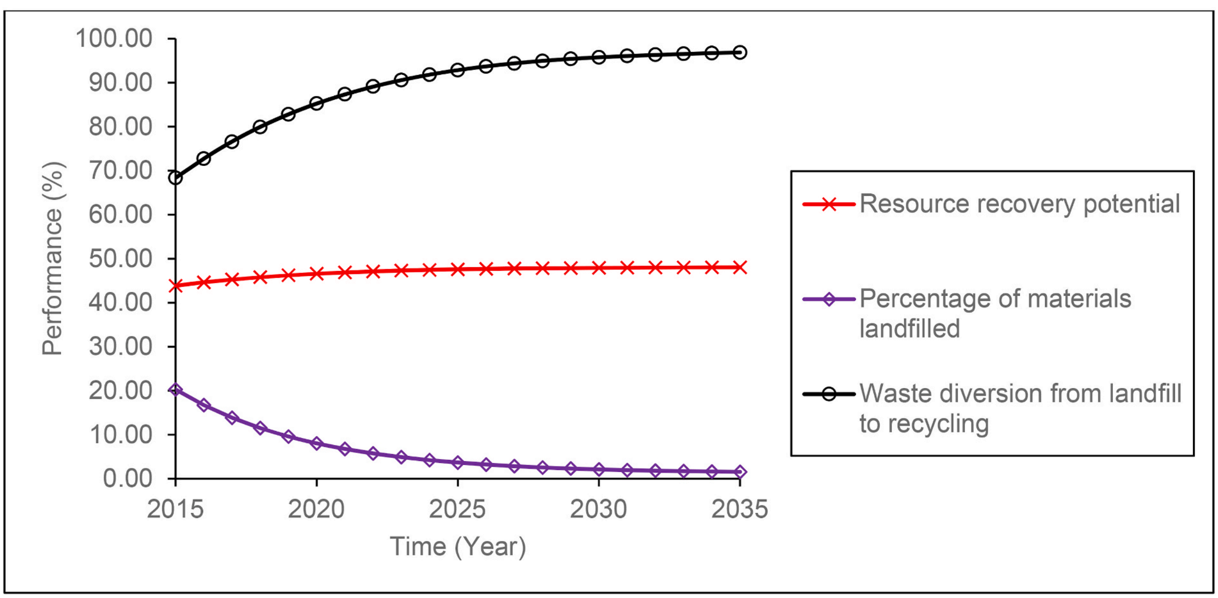
4.3. Economic implications

The economic implications on treatment facilities and local authorities of different scenarios were evaluated by considering capital costs and gate fees of different treatment facilities. The capital costs refer to the public and private investment made on the treatment facilities, while the gate fees refer to the charges paid by the local authorities to the treatment facilities to maintain the operation. The basis used for evaluating the capital costs and gate fees are presented in Table A.15 in the Supplementary Materials. Fig. 6 shows the changes of capital costs (Fig. 6(a)) and gate fees (Fig. 6(b)) from year 2019–2035 due to increased recycling rate and diversion of waste from landfills, and compared the base case with Scenarios 1 and 2. In the base case, an 8.2% reduction of household residual waste to landfills (from 8.5% in 2019 to 0.3% in 2035) can be observed, resulting in an increase in EfW capacity to the same extent (from 46.5% in 2019 to 54.7% in 2035). An additional capital investment of 1644 M£ (from 6627 M£ in 2019 to 8271 M£ in 2035 as shown in Fig. 6(a)) would be needed to cope with the increase of diverted waste from landfills to EfW and the treatment of rising household waste due to increasing population. The increase of capital investment is dominated by EfW (406.9 £/tpa), followed by composting (307.1 £/tpa), AD (207.3 £/tpa) and MRF (187.3 £/tpa) (See Table A15 in the Supplementary Materials). Although more waste has been diverted from landfills in the base case, it has not shown improvement on recycling rate. The additional capital investment is allocated primarily on energy recovery rather than recycling. In other words, it does not support moving the materials up the waste hierarchy towards recycling and reuse. On the other hand, Scenarios 1 and 2 promote recycling of materials from 45% (2019) to 61.9–65.8% (2035) alongside diverting waste from landfills from 8.5% to 0.2% and reduction of household residual waste to EfW from 46.5% to 34–37.9%. An additional capital investment of 709–716 M£ (from 6627 M£ in 2019 to 7336–7343 M£ in 2035 as shown in Fig. 6(a)) would be needed due to higher waste generation and the additional capacity required for recycling and treatment facilities. These alternative scenarios that incur lower capital investment are more compelling compared to the base case in terms of enhancing recycling while reducing reliance on EfW. Note that time value of money has not been considered in this analysis, which implies that the additional capital cost required for 2035 could be greater than the current estimation.

Fig. 6(b) shows the total gate fees in the base case increase by 147 M£/y from 1608 M£/y in 2019 to 1755 M£/y in 2035, despite a considerable reduction (96%) in gate fees for landfills from 223 M£/y to 9.3 M£/y (Note: The gate fees for landfills is 116 £/t inclusive of landfill tax of 91.4 £/t). Diversion of waste from landfills has resulted in an increase of



(a)



(b)

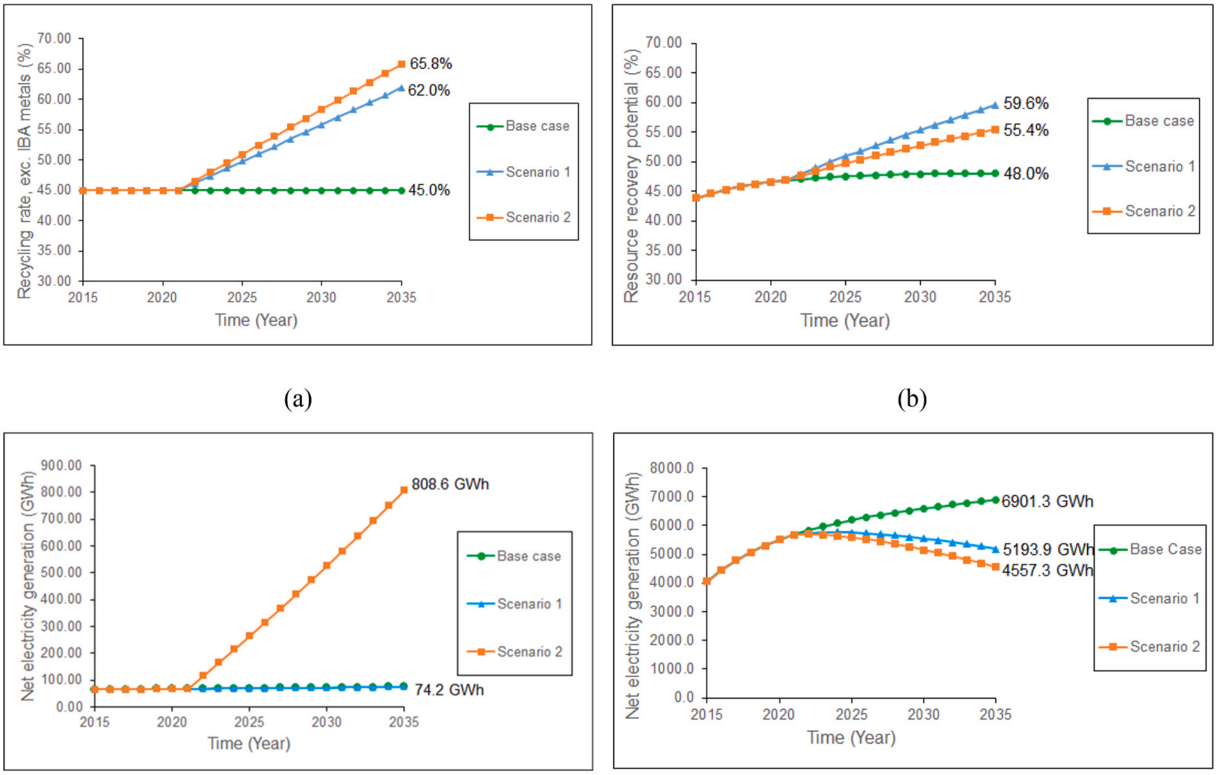
Fig. 4. (a) Upstream performance; and (b) downstream performance of household waste management in England.

310 M£/y on the gate fees of EfW from 974.6 M£/y in 2019 to 1285.2 M £/y in 2035. The gate fees for EfW is the most significant (93 £/t), followed by MRF (43 £/t), composting (37 £/t) and AD (35 £/t) (See Table A15 in the Supplementary Materials). On the other hand, scenarios 1 and 2 are more compelling compared to the base case where 68–156 M£/y reduction in gate fees can be achieved in 2035 compared to 2019. It should be noted that the gate fees also reflect the local authorities' spending on waste management, and it has been assumed that the gate fees remain unchanged for the period of study from 2019 to 2035. Hence, scenarios 1 and 2 that incur lower total gate fees and promote recycling instead of energy recovery, are more favourable compared to the base case.

4.4. Discussion and recommendations

Here, we discuss two important implications of the results presented above, followed by several recommendations.

Over-dependency on EfW: The base case scenario has shown the possibility of achieving 1.5% of materials landfilled and 96.9% of waste diversion from landfill to recycling by 2035, provided that the exponential reduction can be attained (see Fig. 4). Assuming that EfW is the only route to treating residual waste, this implies that a higher capacity of EfW would be needed to cope with the increasing amount of waste diverted from landfills. In the present study, it has been predicted that the amount of residual waste (directly from household and rejected materials from other treatment facilities) sent to EfW would increase from 8.8 Mt in 2015 to 15 Mt in 2035 (see Supplementary Materials,



(c) (d)

Fig. 5. Comparison of scenarios based on (a) recycling rate (exc. IBA metals); (b) resource recovery potential; (c) net electricity generation from AD; and (d) net electricity generation from EfW.

Table A9). This would lead to an increase in energy generation from EfW which in turn provides greater substitution of energy from fossil fuels. It has been predicted that the electricity generated from EfW would be able to reach 2.86% of the total electricity generation in England (241431.4 GWh is the average between 2015 and 2019 (BEIS, 2020) and it has been assumed that the electricity generation in England does not change over time) by 2035 compared to 1.68% in 2015 (see Supplementary Materials, Table A9).

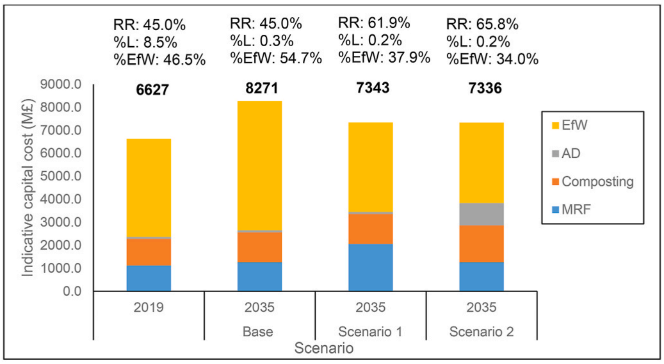
Distorted significance of IBA: If EfW is to significantly expand in the waste management system, the recovery of IBA metals from EfW would also increase, which has a positive impact on the recycling rate if IBA metals are included. It should be noted that there is a discrepancy between the results predicted in this study compared to DEFRA's data for IBA metal recovery, and this has been adjusted using a factor of 0.58 using residual sum of square method (see Supplementary Materials, Figure A3). The two indicators, recycling rate (upstream) and resource recovery potential (downstream) provide different insights into the performance of waste management system. Strictly speaking, recycling rate including IBA metals is considered as a hybrid indicator (both upstream and downstream). Including IBA metals in the recycling rate calculation has the advantages of effective monitoring the resources that are recovered after residual waste treatment and helps meet the target, however, this in some ways is encouraging more residual waste to be treated via EfW in order to meet the target. If the waste management system under current conditions (i.e. constant waste composition, collection rate and available treatment technologies) remain unchanged, then achieving the recycling target (with the current definition) would strongly rely on recovering more IBA metals, considering that EfW is the only path that the residual waste can be diverted to and treated by.

Based on the modelling results and the above discussion, the following recommendations are made for the future waste management authorities to consider:

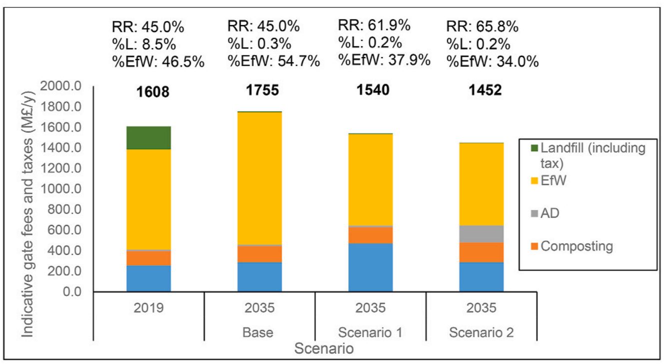
Reducing future reliance on EfW: Heavy reliance on EfW should be re-considered as this is not a sustainable pathway towards circular economy. Producing electricity via waste incineration results in twice the carbon intensity (580 g CO_{2eq}/kWh) compared to the average carbon intensity of the EU28 electricity grid (296 g CO_{2eq}/kWh) (Vähk, 2019). Furthermore, insufficient heating network in England also leads to excess heat generated from EfW being wasted. Transforming from linear to circular economy via improvement on recycling and returning the materials back to the loop to reduce natural resource consumption and minimise waste should be promoted (Ng et al., 2019; Ng and To, 2020). A robust resource recovery from waste strategy should follow the waste hierarchy principle considering prevention, reuse, recycling and recovery of materials through different treatment pathways before disposing to landfills.

Reconsidering the key metric to guide policy and practice: Resource recovery potential, proposed in this study, is a more effective indicator compared to recycling rate. Resource recovery potential takes into account all the resources that can be recovered at the downstream treatment processes. This indicator, as well as waste diversion from landfill to recycling, can be used in conjunction with recycling rate to give a more realistic waste management performance and the state of resource recovery. It should be noted that diverting more waste from landfills does not necessarily imply an increase in recycling rate or resource recovery potential to the same magnitude. Recycling rate relies on collection efficiency and segregation on the upstream which is very much driven by the household behaviour. On the other hand, resource recovery potential depends on the quality/composition of input waste stream and the efficiency of the treatment facilities.

Advancing the management of food and organic waste: Achieving



(a)



(b)

Fig. 6. Economic implications of increasing recycling rate and diversion of waste from landfills. (a) indicative capital cost; and (b) indicative gate fees and taxes. RR: recycling rate (excluding IBA metals); %L: percentage of household waste landfilled; %EfW: percentage of household waste sent to EfW.

the recycling target of 65% by 2035 depends on the efficiency of recovering fractions of materials embedded in the residual waste streams. Based on the scenario analysis in section 4.2.2, it is likely to meet the recycling target if the food and organic waste fraction (scenario 2), the largest fractions in the residual waste stream in the context of England, can be fully recycled. The current route of recycling has limited capability for material valorisation. Food and organic waste treatment through composting and AD gives low-value products such as fertilisers, heat and electricity.

Promoting circular economy through advanced resource recovery systems: There are also inherent limitations in MRF for achieving greater material recovery due to the contamination level in the incoming waste streams, resulting in significant amount of materials being rejected (Ng and Phan, 2021). Robust resource recovery systems such as an integrated material recovery and reject valorisation system (Ng and Phan, 2021; Ng et al., 2021) are currently lacking in England and thus rejected materials are often sent to landfills or EfW. Whilst EfW could be a feasible option in a short term to effectively divert waste from landfill, it does not help boosting material recovery and achieving circular economy in long term. Policy intervention and innovative solution to sustainable waste management strategy in England is urgently needed. This can be achieved by promoting material recycling and waste valorisation (e.g. chemical recycling of plastic waste, jet fuel and hydrogen from MSW, and CO_2 capture and utilisation) in lieu of energy recovery from waste.

5. Conclusions

This paper presents a comprehensive system model using stock-and-flow diagram for household waste management, exemplified using the waste management scenario in England. The stock-and-flow diagram illustrates upstream waste generation from household to downstream treatment (i.e. recycling and recovery) and disposal of waste, and includes products, rejected materials and emissions/discharge/losses generated from waste treatment facilities. These were modelled through three integrated modules, i.e. household waste generation and collection; waste treatment and disposal; and energy recovery modules. A detailed mass and energy balance has been established and the waste management performance has been evaluated using six indicators, i.e. recycling rate; percentage of household waste landfilled; percentage of household waste sent to EfW; resource recovery potential; percentage of materials landfilled; and waste diversion from landfill to recycling.

This study indicates that, if the current household waste composition remains unchanged (i.e. no policy or behavioural changes to improve separate collection), the targeted recycling rate of 65% by 2035 will not be met. Nevertheless, it is still possible to achieve less than 10% of total waste to landfills if the current rate of waste diversion can be improved exponentially. Alternative scenarios show that it is likely to meet the recycling target of 65% if the food and organic waste fraction in the residual waste stream can be fully recovered. Furthermore, resource recovery potential can potentially reach nearly 60% if all dry recyclables in the residual waste stream can be fully recovered. It is inevitable that the capital investment on EfW will increase between 2019 and 2035 if there is an increase in waste generation due to the rising population and thus more waste is diverted from landfills as predicted in this study. However, the increase in capital investment will largely depend on the resource recovery strategy. This study estimated that an additional capital investment of 1644 M£ would be needed if the current separate collection practice remains unchanged. If dry recyclable or food/organic waste fraction in the residual waste stream can be recovered, then more materials can be recycled through MRF, AD and composting, and less waste will need to be treated in EfW. In that case, an additional capital investment of 709–716 M£ would be required. In conclusion, improved resource recovery practices through recycling can reach at least 60% recycling rate by 2035 and requires only half of the additional capital investment needed for energy recovery.

Resource recovery potential can be a useful indicator that is complementary to recycling rate as it is capable of monitoring the amount of materials that can be recovered at downstream treatment, in addition to measuring the amount of household waste that is prepared for recycling. For the case of England, diverting more waste from landfills to EfW could be effective in short term. However higher capital investment and gate fees would be incurred, and fundamentally it is not a sustainable pathway. In light of the goal of achieving a more circular economy, enhancing material recovery through reuse and recycling, reducing reliance on EfW and deploying more robust waste valorisation technologies should be considered in future policy and planning for waste management in England.

The model offers a reliable tool for analysing future waste generation and treatment scenarios, enabling recommendations to be drawn based on the forecast on different performance indicators. However, it should be recognised that the model and prediction are limited in that (i) the same performance has been assumed for each treatment plant and there is a lack of industrial data to validate the performance of the downstream treatment sites; and (ii) it only considers technical performance of the waste management system. Future work will aim at addressing these limitations by considering (i) variability on the efficiency of treatment plants; and (ii) economic, environmental and social variables in the model. The model will be further developed to examine detailed environmental impact associated with waste management, by including greenhouse gas emissions (e.g. methane gas from landfills); contaminants to land, water and air; and nutrient flows such as nitrogen and phosphorus, at local and regional scales. In addition, the model will be enhanced to explore the effect on waste management efficiency by including factors such as social acceptance and policy changes.

Credit author statement

Kok Siew Ng: Conceptualization, Validation, Formal analysis, Investigation, Writing – Original Draft, Visualization, Funding acquisition, **Aidong Yang:** Validation, Writing – Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116585.

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