A Systems Thinking Approach to Stimulating and Enhancing Resource Efficiency and Circularity in Households

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Abstract

Households are highly resource intensive in terms of energy consumption and waste generation, and resource utilisation and management in households has wider implications at the national level. This paper applies systems thinking using a circular economy approach at the household level for the first time. The approach takes into consideration energy supply and demand, waste management and resource recovery from waste in a single system. Combining energy and waste management analysis enables better understanding of the systems at household level and can address resource efficiency, fuel poverty and environmental issues more effectively at the national level. This study adopts the Systems Thinking Approach to Resource Recovery (STARR) framework to identify the potential improvements that can be made within the system. Three models of households on energy and waste management, including "waste-and-energy", "waste-to-energy" and "reduced consumption" models, are examined through assessments of economic, environmental and social dimensions. These models are further explored through different scenarios, by considering the adoption of renewable solar photovoltaic (PV) energy supply, increasing recycling rate, integrating energy from waste into household and reducing consumption of resources and waste generation. The scenario with the least environmental impact involves adopting a concerted approach through switching to solar PV, increasing recycling rate from 45 to 60% and sending 100% of residual waste into energy recovery (i.e. within the "waste-to-energy" model), with global warming potential (GWP) of −1308 kg CO_2-equivalent/year and total saving/income of £680 per year, on a one household basis.

Keywords: material flow analysis; circular economy; LCA; sustainability assessment; net zero; solar PV.

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1. Introduction

The UK has set an ambitious target to reach net zero in greenhouse gas (GHG) emissions by 2050 as a significant step forward in response to the Paris Agreement 2015 and Intergovernmental Panel on Climate Change (IPCC)'s goal of limiting the global average temperature rise to 1.5°C [1-3]. In the UK, GHG emissions associated with the energy consumption from the residential sector is 65.9 Mt CO_2-equivalent, contributing 18% to the total GHG emissions of 364.1 Mt CO_2-equivalent in the UK [4]. The increasing demands of energy and accompanying emissions will be a continuing concern to the nation unless significant reduction of GHG emissions takes place. Such stringent climate change mitigation targets can only be realised if deep decarbonisation (a concerted approach in transitioning to low-carbon economy through technological, socio-economic and policy pathways) is undertaken in all sectors to achieve a GHG emission reduction of at least 40 Gt CO_2-equivalent per annum [5]. Deep decarbonisation requires revolutionary transformation in energy systems to achieve greater enhancement in energy efficiency and steep reduction in carbon intensity (i.e. CO_2 emissions per unit of energy consumed or economic activity) [6]. Development and adoption of low-carbon technologies as well as changing of household consumption patterns and individual behaviours, together with the support of government policies are essential to achieving the net-zero target.

According to the latest UK Department for Environment, Food & Rural Affairs (DEFRA)'s Digest of Waste and Resource Statistics, waste arising from households ("household waste" has been adopted consistently in this study to avoid confusion) was estimated to be 27.4 million tonnes a year in 2016 [7], corresponds to 2.76 kg/household-day or 1.14 kg/capita-day. The UK is obliged to meet a minimum recycling target of household waste of 50% by 2020 (Note: a revised target of 65% by 2030 has been proposed) according to the EU Waste Framework Directive (2008/98/EC) [8]. The UK recycling rate has reached 45% (excluding incineration bottom ash) in 2017 compared to 40.4% in 2010 [9], yet significant efforts are still required to meet the national/EU target. This also implies that significant value from waste has not been recovered and the concept of resource recovery from waste has not been well appreciated at household level.

Addressing the energy and waste issues at the household level independently without a holistic view of the problems and understanding of interdependencies between the systems may lead to missed opportunities for optimum use of resources. A systems thinking approach to circular economy needs to be established at household level, taking into consideration energy supply and demand, waste management and resource recovery from waste in a single domain, which so far has not been investigated. Systems thinking involves the consideration of multiple perspectives at its core, the interconnectedness of the different associated components constituted to a problem and multi-stakeholder collaboration to tackle complex problems and decision-making. Bosch et al. [10] proposed a systems thinking approach to addressing agriculture and natural resource management issues and investigated different case studies in Australia, Cambodia and the Philippines. Ng et al. [11] developed systems thinking methodologies and explored the sustainability impacts through synergistic utilisation of organic resources (i.e. food waste) from households and supermarkets. These studies demonstrated that improving the existing resource management practices requires different parts of a system (e.g. stakeholders, technological processes) to be integrated and the three main dimensions of sustainability (i.e. economic, environment and social dimensions) to be taken into account.

Conventionally and even until today, energy and waste management in household have been treated as independent domains. In relation to research in the energy domain (activities or processes related to consumption and production of energy), there are numerous optimisation studies [12-14] that focus on identifying the best form of energy supply system for households through minimising operation cost and environmental emissions. Üçtuğ and Azapagic [15] examined the environmental impacts of adopting residential-scale integrated solar PV-battery system in households in Turkey and concluded that the resulting impact is 1.6–82.6 times lower than grid electricity. Golmohamadi et al. [16] studied the interaction between thermal-electrical characteristics of household appliances, the uncertainty in market retail prices for solar/wind electricity and the impact on power distribution network. A systems thinking approach was embedded in this study, however it has only explored the cost implication without considering environmental and social impacts. Most of the above studies have only considered cost and/or environmental implications. To the best of our knowledge, only the study by Vogt Gwerder et al. [17] has considered all three dimensions of sustainability. The authors have adopted the life cycle sustainability assessment (LCSA) and Multi-Criteria Decision Analysis (MCDA) approaches in examining the trade-offs between economic, environmental and social impacts of supplying the electricity and heating needs in two off-grid households in rural Portugal. For research related to waste domain (activities or processes related to generation and management of waste), Jeswani and Azapagic [18] conducted a detailed life cycle assessment (LCA) to compare the environmental sustainability of energy recovery scenarios including recovery of biogas from landfill or incineration, but this was conducted at national level. Jamasb and Nepal [19] studied the economic and environmental costs and benefits of waste-to-energy strategy and suggested that it plays a key role in both waste management and renewable energy policies in the UK. So far, studies on household waste minimisation and resource recovery are scarce. Overall, most of the studies are focused on either energy or waste domain but none of them have explored both energy and waste domains using a holistic approach. Given that there is a lack of holistic understanding on resource management from a household perspective and the associated sustainability impacts on the whole system, there is an opportunity to address this gap of knowledge through examining both of these domains using a systems thinking approach, proposed in this paper.

In this study, a tri-lateral approach in systems thinking, presented in Figure 1 has been proposed and employed to identify the potential of energy efficiency and resource circularity enhancement in households. Circular economy is "an industrial system that is restorative or regenerative by intention and design" [20]. This suggests that waste can be used as resources and should be maintained in a loop in view of reducing virgin materials and energy and lessening the environmental burden associated with resource extraction, production, consumption and disposal [20]. Circularity in the present context implies that the linear resource production-consumption-disposal pattern is reconfigured into loop by returning the resources embedded in waste stream generated from households into useful product such as energy that can be consumed in a household. As a result, this would reduce the overall resource use and environmental impact. This research addresses United Nations Sustainable Development Goals (SDG) 7 on *Affordable and Clean Energy* and SDG 12 on *Responsible Consumption and Production* [21] in an integrated way.

The aim of this research is to explore the alternative strategies for improving resource utilisation in households while reducing costs and emissions. The following research questions will be answered in this study:

(a) What are the potential economic, environmental and social impacts on household if grid electricity supply is switched into on-site renewable electricity generation?
(b) What are the potential economic, environmental and social impacts on household if recycling rate is increased?
(c) What are the trade-offs on the economic, environmental and social dimensions if energy and waste domains are considered holistically within a single system from the household perspective?

The objectives of this study are to establish a new household resource management model by applying systems thinking approach and provide evidence-based recommendations for improving energy and waste management in household based on the potential impacts associated with economic, environmental and social dimensions.

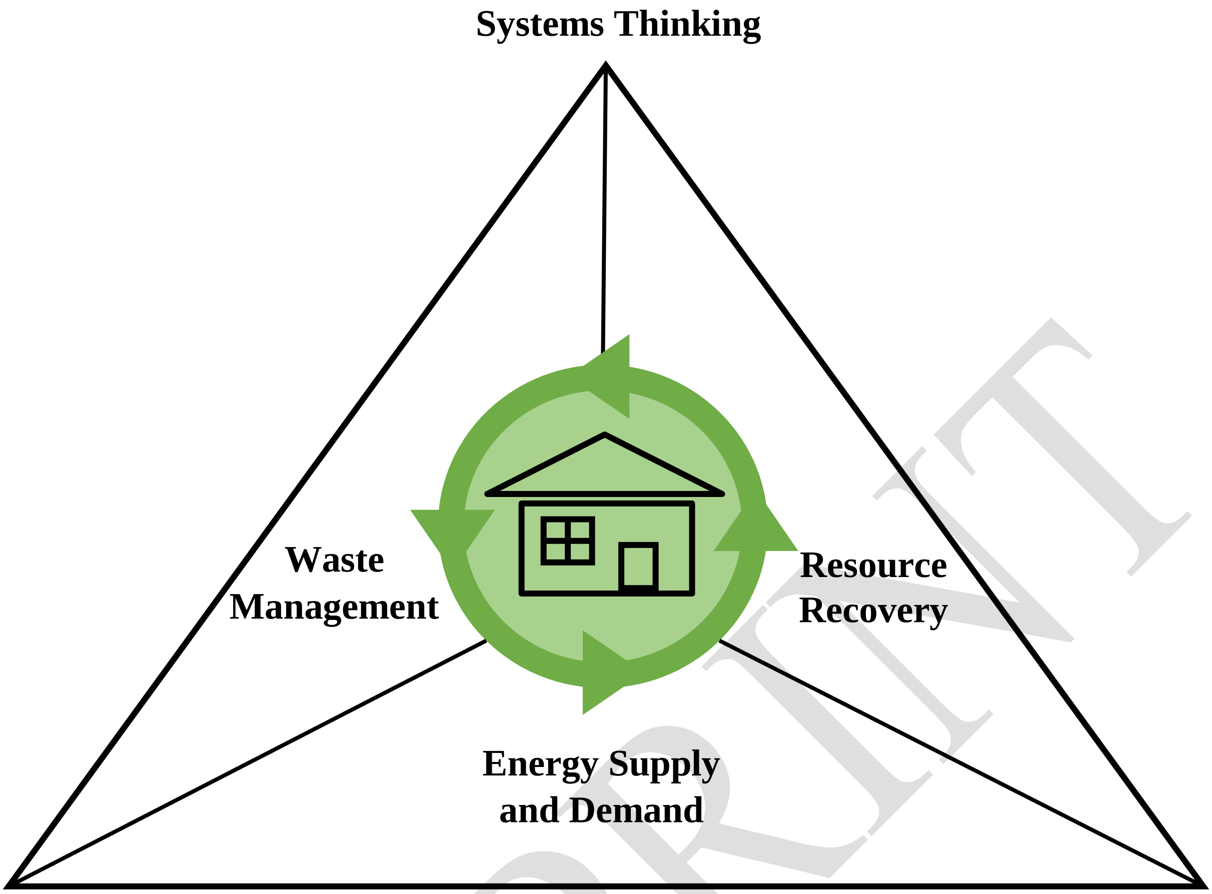


Figure 1: Conceptual diagram showing tri-lateral approach in systems thinking for enhancing energy efficiency and resource circularity in households.

2. Methodology

The Systems Thinking Approach to Resource Recovery (STARR) framework (Figure 2) proposed by Ng et al. [11] has been adopted in this study to analyse and identify the potential improvement that can be made by considering the energy and waste domains of household as a whole system. The framework consists of: (1) system analysis; (2) scenario creation; and (3) sustainability assessment. The principles and details of development of the STARR framework can be found in [11]. The original STARR framework was developed to address waste management only and thus has been modified to suit the present context of combining both energy and waste domains.

System analysis: Material flow analysis [22], a systematic tool for the examination of the quantity (i.e. level of energy consumption / waste generation) and quality (i.e. waste composition) of the resources within the designated system boundary, has been conducted using Sankey diagrams for both energy and waste domains. The main implications that can be derived from the material flow analysis are: (i) the source of energy supply (source analysis); (ii) the availability of waste for resource recovery from different categories of waste streams (source analysis); (iii) the level of energy consumption (sink analysis) and (iv) the flows of waste to different treatment/disposal routes that determine the maximum resource recovery potential (sink analysis). The system analysis of resources enables pragmatic scenarios to be created and further supports informed decision-making.

Scenario creation: Scenarios have been developed to explore business-as-usual system as well as alternative systems by considering (i) source of energy supply; (ii) recycling rate; and (iii) resource consumption. For the business-as-usual scenario, energy demand in household is supplied through grid electricity while the most recent household recycling rate (excluding incineration bottom ash) in the UK (2017) has been adopted. This will be discussed in detailed in section 3.5. Alternative systems include (i) "waste-and-energy" model where improvements are made independently on individual domains of energy and waste in household (i.e. without the perception that energy can be recovered from waste); (ii) "waste-to-energy" model where a holistic approach is used to improve the energy and waste domains in households (i.e. with the perception that energy can be recovered from waste); and (iii) "reduced consumption" model where energy consumption and waste generation from household are reduced. Systems thinking has been embedded within "waste-to-energy" scenario by considering circular economy strategy [20] and design for sustainability principles [23]. The objective is to promote efficient resource utilisation and waste diversion from landfill through enhancing recycling and recovery practices and thus improving the resource efficiency of the system.

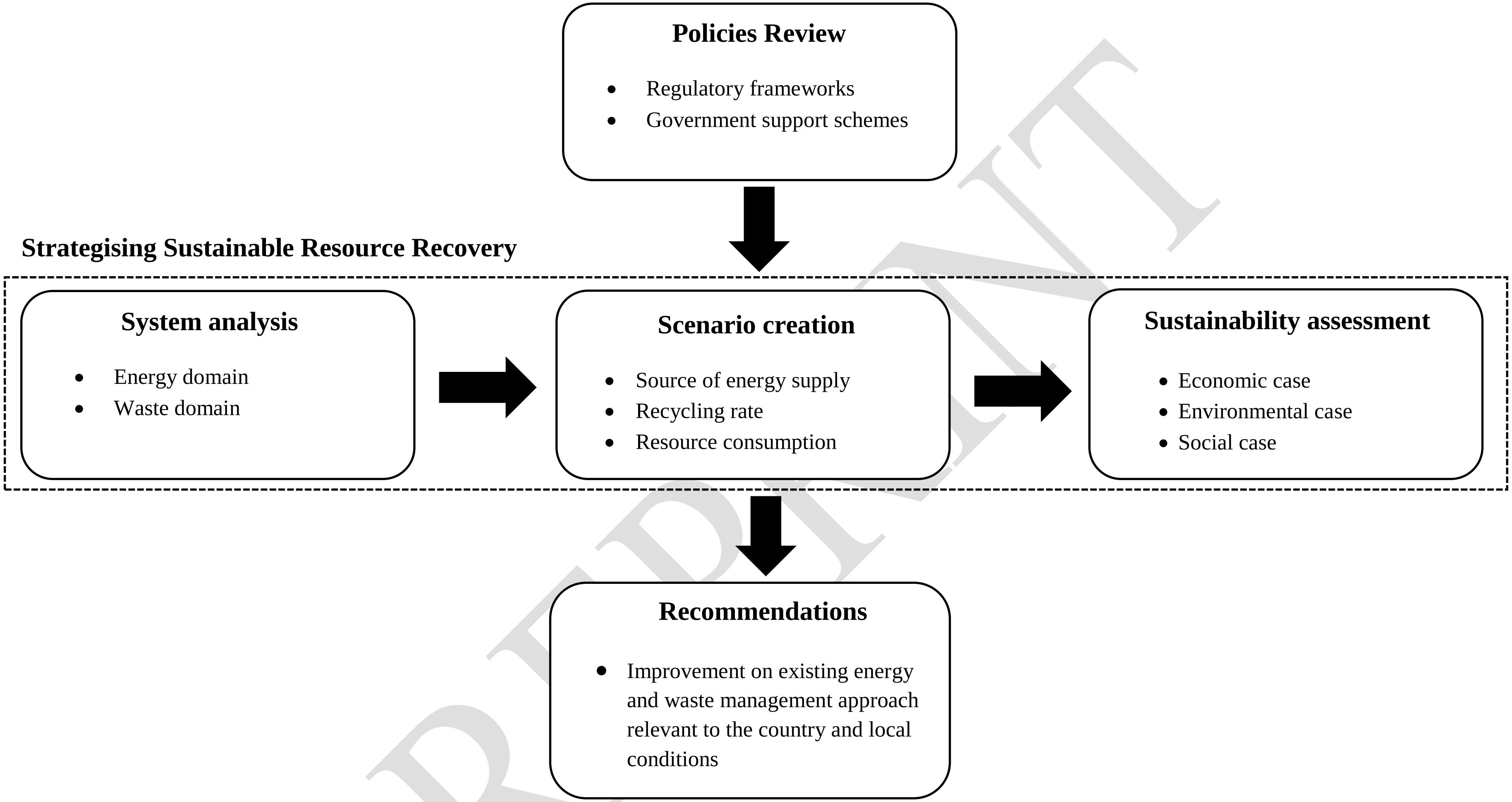


Figure 2: Framework for systems thinking approach to resource recovery (STARR) [11].

Sustainability assessment: The economic, environmental and social impacts of each scenario have been examined using sustainability assessment [24-26]. The assessment enables us to make sound decisions and assertions of what action should be taken in order to make the system more sustainable.

The economic impact of the scenarios was assessed using cost-benefit analysis in this study. This included the evaluation of (i) annual electricity cost per household; (ii) indicative value of waste per household per year; and (iii) the annual cost saving potential per household (inclusive of fiscal incentives).

The environmental impact was assessed using environmental LCA, which systematically quantifies the resource use and emissions resulting from various activities and processes considered within the system boundary. In this study, LCA has been conducted according to the ISO principles and framework laid out in ISO 14040:2006 which comprises four evaluation phases: (i) goal and scope definition; (ii) inventory analysis; (iii) impact assessment and (iv) interpretation [27]. SimaPro 9.0 software has been employed to conduct the LCA for energy consumption and waste generation scenarios. This study considers a comprehensive range of impact categories which goes beyond the standard carbon footprint assessment specified in PAS 2050 [28] and GHG Protocol [29].

(i) Goal and scope definition

- Goal statement: The goal of this LCA study is to determine the trade-offs in environmental impacts if a household is to adopt a "waste-and-energy", "waste-to-energy" or "reduced consumption" model.
- Functional unit for energy consumption scenario: Production of 1 kWh of electricity
- Functional unit for waste generation scenario: Treatment of 1 kg of household waste
- System boundary: The boundary of study includes the generation of grid electricity or electricity generation from solar PV, waste treatment/disposal/recovery/transportation, where household is placed at the core. Figure 3 illustrates the system boundary and life cycle stages of the energy and waste domains in households examined in this study.
- Allocation method: product substitution. This method implies that the environmental burdens are allocated proportionally to specific processes.
- Assumptions: The assessment assumes steady-state energy consumption level and waste generation using an average value per household (i.e. total national energy

consumption/waste generation divided by total number of households in the country). The number of occupants, type and size of household, appliances, nature of activities in the household or associated with household have not been considered due to high level of variability across each individual household.

(ii) Inventory analysis

- The inventory data from Ecoinvent 3.5 database embedded in SimaPro 9.0 has been employed.

(iii) Impact assessment

- CML-IA baseline V3.05 / EU25 has been selected because it is widely adopted in many LCA studies for mid-point impact assessment. The impact categories under consideration include: abiotic depletion potential (ADP); global warming potential (GWP); ozone depletion potential (ODP); human toxicity potential (HTP); freshwater aquatic ecotoxicity potential (FAEP); marine aquatic ecotoxicity potential (MAEP); terrestrial ecotoxicity potential (TEP); photochemical oxidant creation potential (POCP); acidification potential (AP); and eutrophication potential (EP).
- ReCiPe 2016 Endpoint has been adopted for examining the damage impact to human health. The default "Hierarchical" method [30] which considers the timeframe applied in most common policy principles was used. This impact category arising from multiple causes such as climate change, exposure to toxic chemicals and particulate matters, and ozone layer depletion has been quantified using the metric of Disability-Adjusted Life Year (DALY). DALY represents the years of life lost due to a combination of premature death and disease.

(iv) Interpretation

- The results from impact assessment have been presented in detailed table format and have further been refined to presentable format using bar charts in view of analysing the results across different scenarios more effectively and drawing conclusions.
- Dominance analysis has been performed for each impact category to examine the magnitude of impact for each scenario.

The social impact of each scenario was assessed by considering public acceptance and participation which influences the transformation in technology uptake and resource management practices. Public acceptance and participation is the key consideration in implementation of new household resource management models [24, 31]. In this context, the contributing factors for increasing the uptake of renewable energy technology and recycling rate have been discussed.

Sources of data

Energy consumption: For energy-related information, the present study has adopted secondary data from the UK Department for Business, Energy and Industrial Strategy (BEIS). BEIS published data on annual electricity consumption based on household type and appliance as well as domestic energy prices [32-34]. Ofgem also provides information on Feed-in Tariff (FiT) rates and representative estimated value of household electricity consumption that has been widely adopted in the energy retail market [35, 36] (Note: the analysis was conducted in 2019 before FiT was phased out). The cost data for solar PV has been obtained from BEIS [37].

Waste generation: Waste data including flow and composition have been obtained from the *Digest of Waste and Resource Statistics* published by DEFRA [7]. This is a secondary source of data and contains most of the required information for different waste streams. However, the compositional data for residual waste stream has not been found from DEFRA's publication and hence the data from VALORGAS (an EU FP7 project) report has been adopted [38]. The average prices paid for collected recyclable materials such as metals, glass, papers and cards and plastics have been obtained from Letsrecycle.com [39]. The waste management costs embedded in the council tax bill has been estimated based on the information published by Oxfordshire County Council [40].

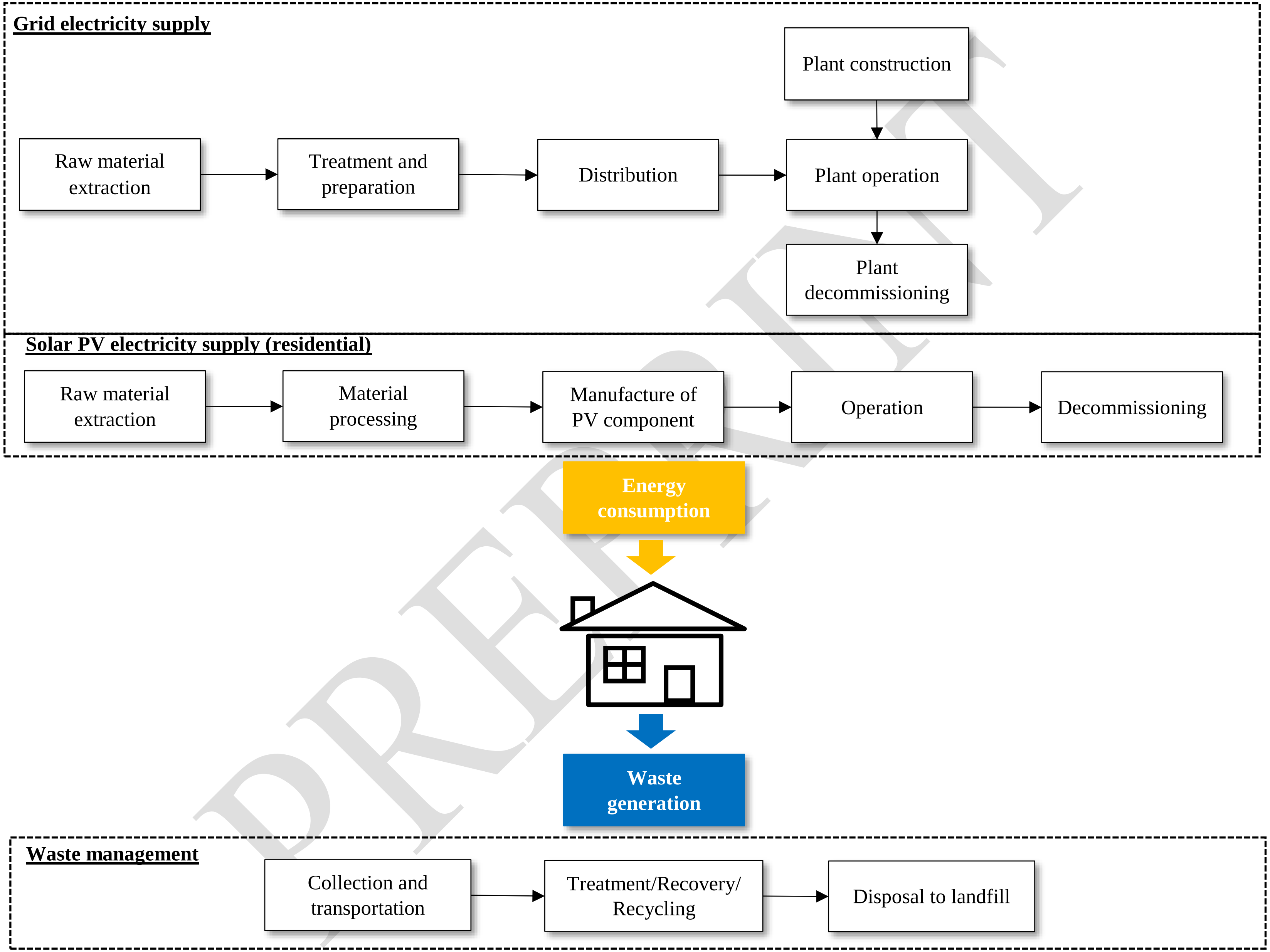


Figure 3: Life cycle stages of electricity generation and waste management in household.

3. Case Studies

3.1 Policy review

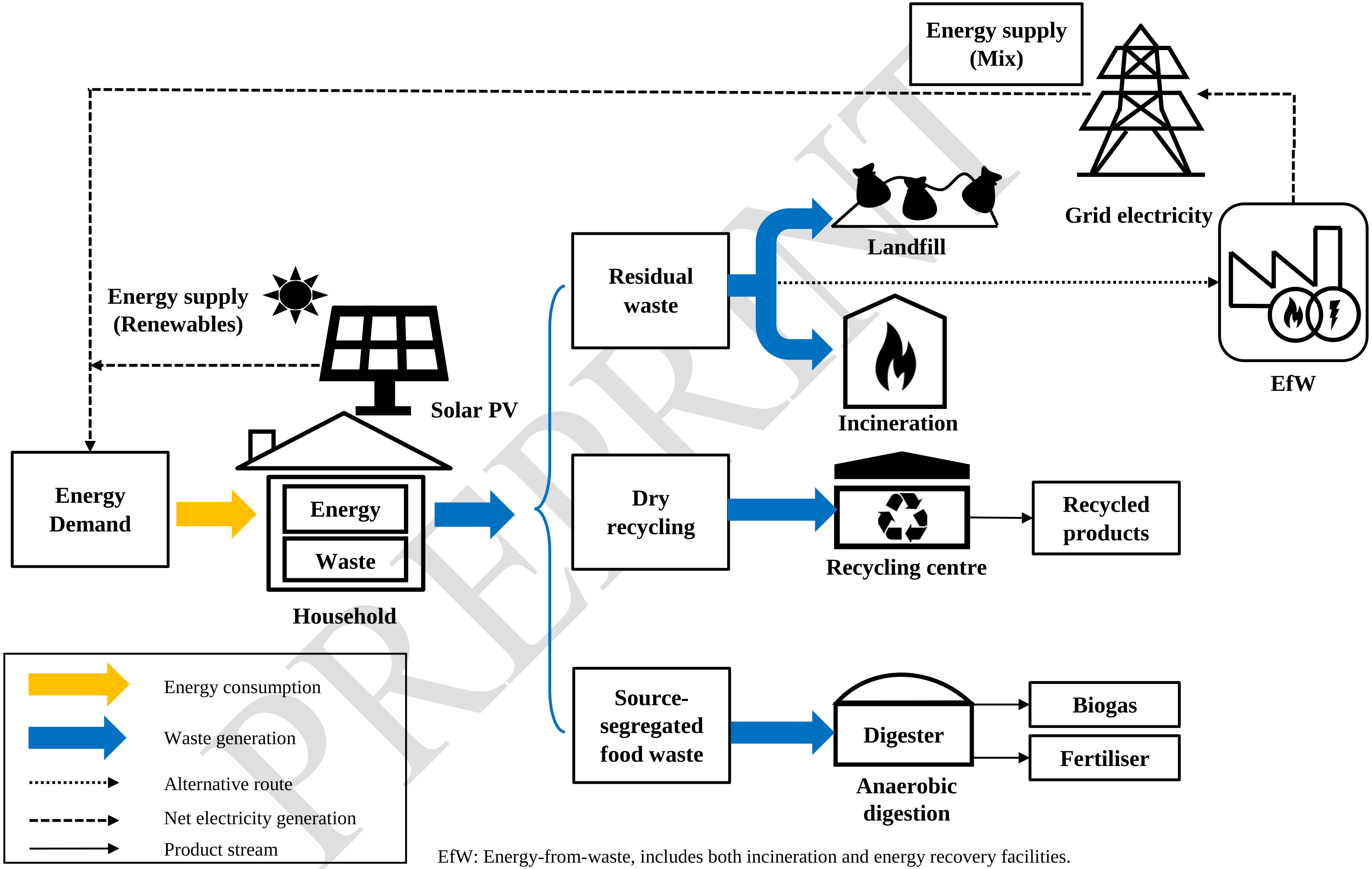
The National Renewable Energy Action Plan for the United Kingdom has set out the targets of delivering 15% of energy from renewables by 2020 [41], guided by the Renewable Energy Directive 2009/28/EC [42]. During the transition period of exiting the EU, the UK has produced a draft integrated National Energy and Climate Plan (NECP), however, the UK contribution towards meeting the 2030 targets for renewable energy and energy efficiency remain unspecified [43, 44]. In the dimension of decarbonisation, the UK is legally bound to Climate Change Act 2008 to meet the net-zero target by 2050 [1].

The UK waste management policies are influenced by the EU Waste Framework Directive (2008/98/EC) [8] which deals with general mixed waste. Under the Directive, the UK is required to meet a minimum 50% recycling target of household waste by 2020 (Note: a revised target of 65% by 2030 has been proposed) and follow the waste management hierarchy of prevention, reuse, recycling, recovery and disposal [8]. The waste hierarchy has been incorporated into the UK legal framework through the Waste (England and Wales) Regulations 2011, the Waste Regulations (Northern Ireland) 2011, and the Waste (Scotland) Regulations 2012. The UK is also obliged to meet the reduction targets of biodegradable municipal solid waste going to landfill of 75% by 2000, 50% by 2013, 35% by 2020 and 10% by 2030 as set out in the EU Landfill Directive (Directive 1999/31/EC) [45], compared to the 1995 baseline level. Apart from Wales which has achieved a recycling rate at 57.1% in 2017, England, Scotland and Northern Ireland with recycling rates between 43.4-46.3% requires significant effort in improving their recycling rates in order to meet the target. This could be due to a number of barriers such as poor segregation at source, poor collection system for collecting recyclable items, increased occupancy of dwellings, social deprivation and ineffective policy levers [46, 47].

3.2 Household systems analysis

The application of systems thinking approach in addressing energy and waste management from a household perspective is illustrated in Figure 4. In the present context, the household is represented by two resource domains: energy and waste. It has been assumed that there is no interaction between the energy and waste domains in the household, i.e. adjusting the level of energy consumption has no effect on the amount of waste generation and vice versa. The energy demand in household can be satisfied by either grid electricity, residential-scale solar PV or electricity generated from residual waste through Energy-from-Waste (EfW) facilities which includes combined heat and power (CHP) production. The source of energy supply and fuel determine the degree of environmental impact resulting from the system. The level of household energy consumption can be correlated with the type of appliance and the associated cost of household electricity has been estimated and detailed in section 3.3. Waste generation from household includes residual waste, dry recycling and organic waste stream. Residual waste is sent to either landfill or incineration; dry recycling is sent to recycling centre; and organic waste such as source-segregated food waste is sent to anaerobic digestion (AD) where biogas and fertiliser are produced. The details of waste composition and the associated indicative value has been estimated and discussed in section 3.3. Different resource utilisation models have been encapsulated in a range of scenarios, presented in section 3.5.

Material flow analysis has been performed as shown in Figure 5. The energy supply is correlated with different appliance in household which has been categorised into kitchen appliance, general utility, entertainment and ICT, and miscellaneous. Kitchen appliance contributes one-third of the total energy consumption in household and the remaining categories of appliance carry almost equal share of energy consumption. Details of the energy consumption based on type of appliance are presented in section 3.4. On the other hand, waste generation from household has been classified into five different categories: food waste, paper and card, glass, metals and plastics. These waste materials are discharged into different waste streams, namely residual waste, dry recycling and organic waste. It can be seen that food waste contribute 43% of the household waste, of which only less than half has been segregated. The material flow analysis also indicates that paper and card distribute evenly between residual waste and dry recycling streams; while 60-70% of glass and metals sent for recycling; and 80% of plastics ended up in residual waste stream. Details of the waste composition and assumptions are discussed in section 3.4.



EfW: Energy-from-waste, includes both incineration and energy recovery facilities.

Figure 4: Household systems thinking mind map.

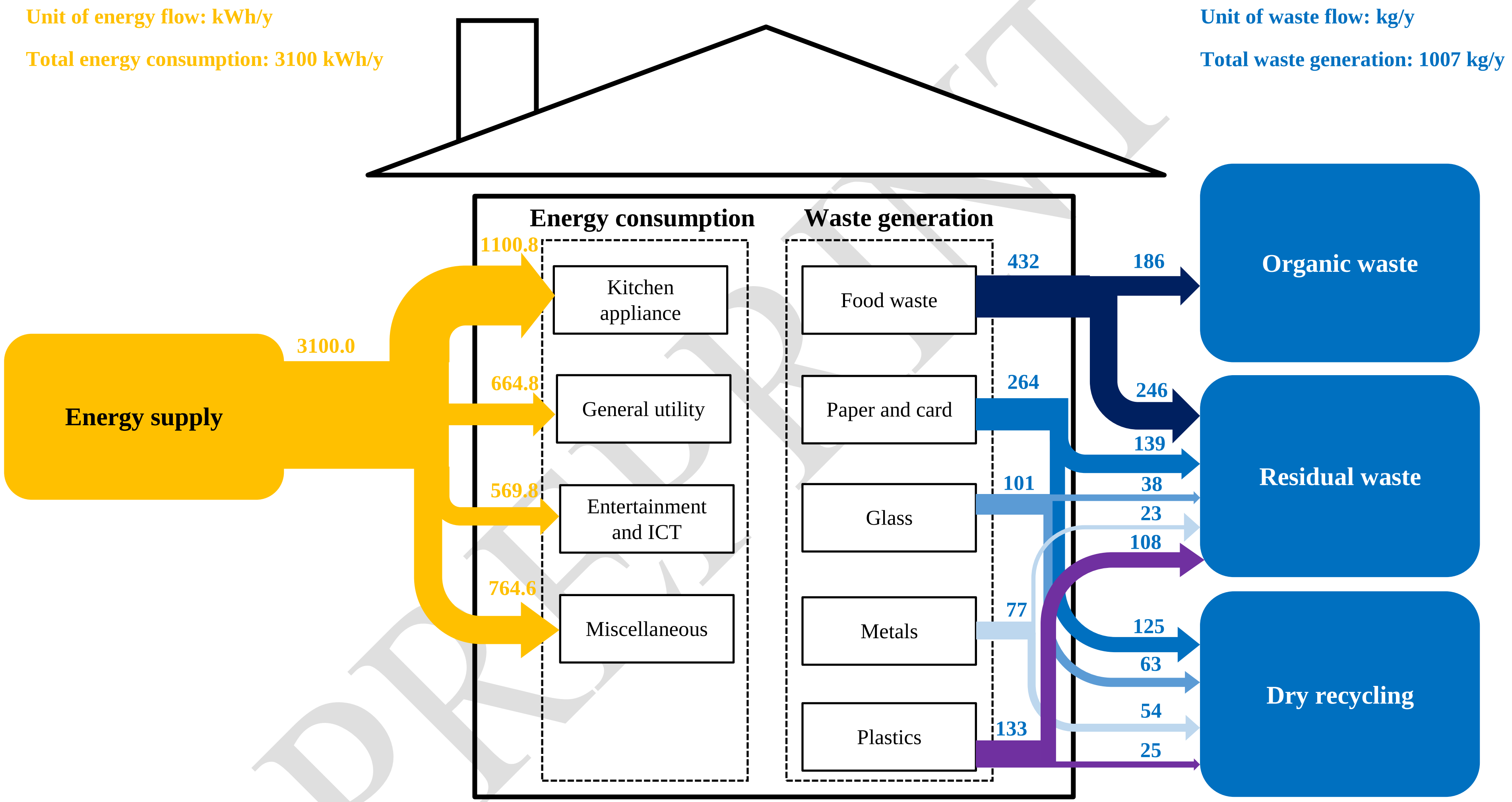


Figure 5: Material flow analysis showing energy consumption and waste generation per household basis.

3.3 Household energy demand and supply

Table 1 provides different estimation of annual UK household electricity consumption and cost based on household types, appliances and consumption data. The electricity cost has been estimated using a unit electricity price of 18 pence/kWh [34]. The summary in Table 1 demonstrates a range of values of annual electricity consumption between 1900 kWh and 4600 kWh per household which associated with annual electricity cost between £342 and £828 per household. The variation in the estimated values are attributed to the data collection and monitoring techniques, household type and occupancy and various consumption patterns. The medium typical domestic consumption value (TDCV) value of 3100 kWh per household estimated by Ofgem has been taken as the basis for subsequent analysis.

Table 1: Range of estimated annual electricity consumption and cost per household in the UK based on different basis of estimation [32, 33, 35].

Basis of estimation	**Data supplier**	**Annual electricity consumption per household (kWh/y)**		**Annual electricity cost per household (£/y)**	**Note**
Household type [(i)]	DECC (now BEIS)	Low	3083	554.94	Data collected from 250 households.
		Average	3567	642.06	
		High	4399	791.82	
Appliance [(ii)]	DECC (now BEIS)	Average	4041.5	727.46	Data collected from 250 households.
Consumption data	Ofgem	Low	1900	342.00	Typical domestic consumption value (TDCV) [(iii)]. Electricity: Profile Class 1. Data collected based on domestic credit meters.
		Medium	3100	558.00	
		High	4600	828.00	

Notes:

[(i)] See Supplementary Materials: Table A.1 for detailed information of annual electricity consumption for each household type.

[(ii)] See Table 2 for the breakdown of electricity use for each appliance.

[(iii)] TDCV is the representative estimated value used in the energy retail market to facilitate communication between suppliers and consumers.

A previous study by BEIS has estimated that an average daily electricity usage of 11.1 kWh, equivalent to 4041.5 kWh annual usage are required for a household in the UK. Table 2 presents a breakdown of the electricity use by appliances, together with the associated costs and GWP (equivalent to GHG or carbon footprint). The results show that kitchen appliances such as refrigerators, cooking stoves, microwaves, ovens, washing machines and dishwasher contribute one-third of the total household electricity use, while audio visual (13.3%) and lighting (10.9%) are also among the largest contributors to the household electricity use.

Table 2: UK household average daily and annual electricity use by appliance.

Appliance (i)	Average daily electricity use per household (ii) (kWh)	Annual electricity use per household (kWh)	Normalised annual electricity use per household (kWh) based on 3100 kWh	% contribution to total electricity use	Cost breakdown based on annual consumption of 3100 kWh (£/y) (iv)	GWP (kg CO_2 equivalent) (v)
Kitchen appliance						
Cold appliance	1.55	567.2	435.1	14.0	78.3	362.0
Cooking	1.21	440.3	337.7	10.9	60.8	281.0
Washing/drying/dishwasher	1.17	427.6	328.0	10.6	59.0	272.9
Sub-total	**3.93**	**1435.1**	**1100.8**	**35.5**	**198.1**	**916.0**
General utility						
Lighting	1.27	464.7	356.5	11.5	64.2	296.6
Water heating	0.23	83.4	64.0	2.1	11.5	53.3
Heating	0.57	207.9	159.5	5.1	28.7	132.7
Showers	0.30	110.5	84.8	2.7	15.3	70.5
Sub-total	**2.37**	**866.6**	**664.7**	**21.4**	**119.7**	**553.1**
Entertainment and ICT						
Audio-visual	1.47	536.5	411.5	13.3	74.1	342.4
ICT (iii)	0.57	206.4	158.3	5.1	28.5	131.7
Sub-total	**2.04**	**742.9**	**569.8**	**18.4**	**102.6**	**474.1**
Miscellaneous						
Other	0.47	173.0	132.7	4.3	23.9	110.4
Unknown	2.26	823.8	631.9	20.4	113.7	525.8
Sub-total	**2.73**	**996.9**	**764.6**	**24.7**	**137.6**	**636.2**
Total	**11.07**	**4041.5**	**3100.0**	**100.0**	**558.0**	**2579.5**

Notes:

(i) Cold appliance, cooking and washing/drying/dishwasher have been categorised under "kitchen appliance"; lighting, water heating, heating and showers have been categorised under "general utility"; audio-visual and ICT have been categorised under "Entertainment and ICT"; and other and unknown have been treated as "miscellaneous" in the material flow diagram shown in Figure 5.

(ii) The data was obtained from 250 households in year 2010/11, monitored over 12 months using meter on total electricity use and most appliances *[32, 33]*.

(iii) ICT: Information and Communication Technology.

(iv) Cost has been estimated based on unit price of electricity of 18 pence/kWh [34].

(v) GWP for producing 1 kWh of electricity is 0.8321 kg CO_2-equivalent using CML method.

Table 3 summarises the installed cost and financial benefits by adopting solar PV of 4 kW installed capacity for a household which requires 3100 kWh of annual electricity supply. The PV of the specified capacity generates approximately 3400 kWh of electricity. By assuming that 100% of the annual electricity demand in household has been supplied from PV (91% usage), while 300 kWh is exported to the grid annually, this gives a total saving/income of £703 per year (including avoided cost for grid electricity and income generated from FiT) with a payback period of 10.6 years. The UK used FiTs to promote renewable electricity generation technologies, including solar PV. FiT consists of generation tariff and export tariff and these have been accounted for based on the installed capacity of the facility. These are the incentives offered to household owners who generates their own electricity and exports the surplus electricity to the grid. However, it should be noted that FiT scheme in the UK closed on 31st March 2019 and may be replaced by Smart Export Guarantee (SEG) scheme. This suggests that household may only be benefited from the avoided cost of electricity bill and thus longer payback period of 13.4 years is expected.

Table 3: Cost associated with PV installation and financial benefits for household.

Specification	Unit	Value
Basis		
PV installed capacity	kW	4 (i)
Annual electricity production from PV	kWh/y	3400 (ii)
Cost		
Total cost of PV	£	7468 (iii)
Financial benefit		
Saving on electricity bill at (avoided cost)	£/y	558 (iv)
FiT, generation (income)	£/y	128.86 (v)
FiT, export (income)	£/y	16.14 (v)
Saving/income for 1 year	£/y	703
Saving/income over 20 years	£	14060
KPI		
Payback time, with FiT	years	10.6 (vi)
Payback time, without FiT	years	13.4

Notes:

(i) Assuming for 1 household; roof space = 28 m^2; 16 × 250 m^2 solar panels [48].

(ii) Estimation based on 850 kWh electricity generation per kW installed capacity [49].

(iii) Calculated based on £1867 per kW installed for size band 0 – 4 kW (mean; March 2019). Cost includes "Cost of solar photovoltaic generation equipment, plus direct costs of fixing panels to roof/ground mount, any performance displays and connecting to electricity supply, including VAT but excluding (a) the cost of any extended warranty; and (b) the cost of any other materials, works or other items whatsoever (such as, but not limited to, any cost of general rewiring at a property or tracker systems). It should be noted that the data are therefore wholesale costs and do not represent the cost that the householder has paid for the installation."[37]

(iv) Based on an annual electricity consumption of 3100 kWh in household and unit electricity price of 18 pence/kWh. See Table 1.

(v) FiT generation = 3.79 pence/kWh; FiT export = 5.38 pence/kWh [36].

(vi) Payback period is calculated by dividing the cost of PV by annual saving/income.

3.4 Household waste management

Household waste in the UK is managed by the local authorities or councils. Council tax bill incorporates the proportion of spending on waste collection, recycling and disposal and is fixed for a specific band of household which is dictated by its property value. Table 4 exemplifies the council tax expenditure on waste management set by Oxfordshire County Council for year 2019-2020 [40]. It has been estimated that each household owner is responsible for an average of £1461 of council tax bill per year of which £87.7 will be used for waste management purposes.

Table 4: Estimation of the proportion of council tax bill relevant to waste collection, recycling and disposal.

Specification	Value	Unit
Council spending (Oxfordshire County Council)	600.3 (i)	million £/y
Percentage of total expenditure on waste disposal and recycling	6 (i)	%
Expenditure on waste disposal and recycling (A)	36.0	million £/y
Amount of household waste	285000 (i)	tonnes
Council spending per tonne of waste	2106.3	£/t
Percentage contribution of council tax towards council expenditure (B)	63 (i)	%
Contribution of council tax towards council expenditure	378.2	million £/y
Number of households (C)	258855 (ii)	households
Average council tax contribution per household	1461.0	£/y
Contribution of council tax per household towards waste disposal and recycling (D)	**87.7 (iii)**	**£/y**

Notes:

(i) Values obtained from Oxfordshire County Council [40].

(ii) Based on 2011 Census data [50].

(iii) D = (A × B) / C

Household waste in the UK is categorised into residual waste, dry recycling, other organics and separately collected food waste based on the DEFRA's WasteDataFlow definition [7]. Residual waste consists of the waste from black refuse sacks (regular household collection), household civic amenity waste, bulky waste, and rejects from recycling. Dry recycling refers to materials that can be processed in recycling facilities such as paper and card, glass, plastic, waste electrical and electronic equipment

(WEEE) and scrap metals. Other organics comprises green garden waste, food waste and other compostable waste. In England, residual waste contribute 55% (12.5 million tonnes in year 2016) to the total household waste; followed by dry recycling (6 million tonnes/year, 26.5%); separately collected food waste (3.8 million tonnes/year, 16.8%) and other organics (0.4 million tonnes/year, 1.7%).

Household waste, in the present context, has been categorised into residual waste, dry recycling and organic waste streams. A representative set of composition has been adopted in this study as presented in Table 5 and it has been assumed that:

- The composition does not change over time.
- The same composition of waste stream is generated across all regions in the UK.
- Organic waste stream consists only of food waste. Separately collected food waste has been grouped under this category.
- Textile, sanitary waste, garden waste and other bulky materials (e.g. furniture, wood and mattresses) have been excluded from the analysis since these are highly variable across different types of properties and also lacking accurate quantification for these wastes.

Detailed composition of residual waste and dry recycling streams from the original dataset can be found in Supplementary Materials: Table A.3 and Table A.4, respectively. Table 5 presents the compositions of each representative component in different waste stream from household, the waste flow in annual and daily bases at the national UK and household levels and also the indicative value of the waste streams. The results which reflect the current situation in the UK shows a recycling rate of household waste of 45% has been achieved [7, 9], where dry recycling and organic waste streams are considered as recyclable fractions while residual waste is considered as non-recyclable fraction. Recycling rate is defined as the recycled amount of household waste divided by total amount of household waste excluding certain waste categories such as street cleaning/sweeping, gully emptying, separately collected healthcare waste, soil, rubble, plasterboard and asbestos waste [9, 46]. It should be noted that incineration bottom metals have now been included in the calculation of recycling rate.

The indicative values of each component in the waste stream have been estimated using the average prices paid for collected materials: paper and card (36 £/t based on mixed paper price, November 2018); glass (11 £/t based on mixed glass price, October 2018); metals (947.5 £/t based on aluminium cans price, October 2018) and plastics (15 £/t based on mixed plastic bottles price, October 2018) [39]. It has been assumed that food waste has zero price in the market. As can be seen in Table 5, the value of household waste is dominated by the dry recycling stream (63% of total value, 56.8

£/household-year or 0.16 £/household-day), mainly attributed to the high market price for metals. In other words, the analysis also implies that 28.9 £/household-year or 0.08 £/household-day has been lost. Theoretically speaking, if all the materials from the residual waste stream can be recovered, this means that additional revenue of 28.9 £/household-year × 27.2 million households = 786 million £/year for the whole UK can be created. These results suggests that a higher recycling rate, i.e. shifting of materials from residual waste to dry recycling stream is urgently needed to avoid further economic loss.

Figure 6 shows that a 5% increase in recycling rate can give 3% increase in value of waste from household per year, which is equivalent to 74 million £/year of value generation at national level. The total value of household waste can potentially be enhanced from 85.7 £/household-year (2331 million £/year at the UK level) at 45% recycling rate to 93.8 £/household-year (2551 million £/year at the UK level) at 60% recycling rate. The economic driver for promoting more recycling practices at household is thus significant. It should also be noted that food waste has a zero value as assumed in this analysis which is currently under-valued in the market.

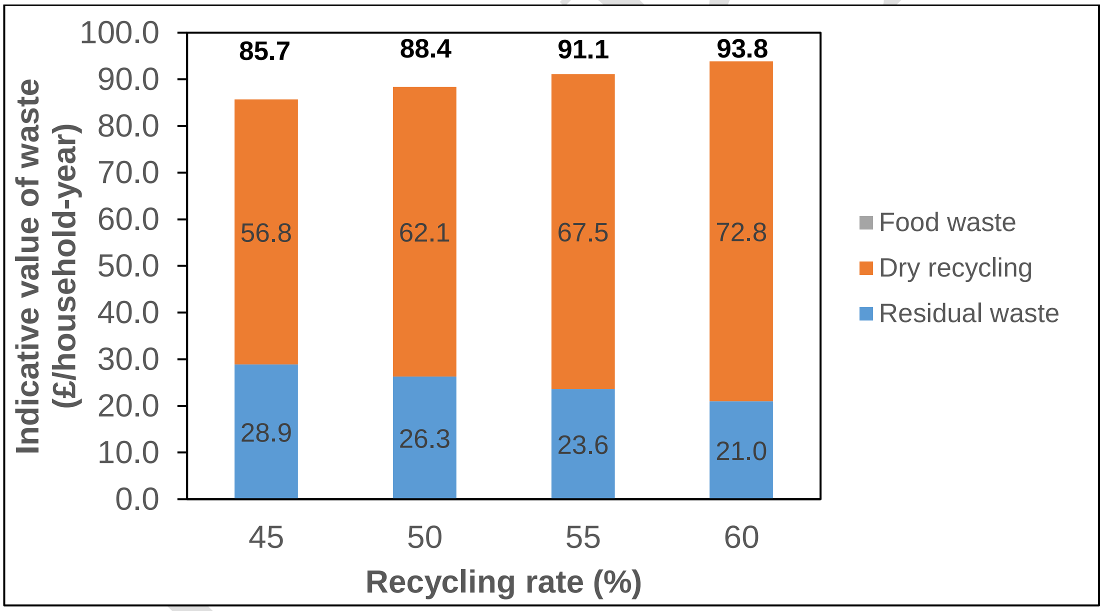


Figure 6: Indicative value of waste from households in response to the increase in recycling rate.

Table 5: Flow, composition and value of waste from households in the UK.

Total household waste	27.4	million tonnes/year (i)
	75068.5	tonnes/day
Number of households in the UK	27.2	million (ii)
Average waste generation per household	1.01	tonnes/household-year (iii)
	2.76	kg/household-day
Breakdown of household waste stream (iv)		
Total residual waste	15.1	million tonnes/year
Total dry recycling	7.3	million tonnes/year
Total organic waste	5.1	million tonnes/year

Category	**Composition** (v)	**Normalised composition**	**Waste flow (annual basis)**		**Waste flow (daily basis)**		**Indicative value of waste**	
	%	**%**	**million tonnes/year**	**tonnes/household-year**	**tonnes/day**	**kg/household-day**	**£/household-day**	**£/household-year**
Residual waste								
Food waste	32.0	44.4	6.7	0.246	18352.5	0.675	0.000	0.00
Paper and card	18.0	25.0	3.8	0.139	10323.3	0.380	0.014	4.99
Glass	5.0	6.9	1.0	0.038	2867.6	0.105	0.001	0.42
Metals	3.0	4.2	0.6	0.023	1720.5	0.063	0.060	21.88
Plastics	14.0	19.4	2.9	0.108	8029.2	0.295	0.004	1.62
Sub-Total	**72.0**	**100.0**	**15.1**	**0.554**	**41293.2**	**1.518**	**0.079**	**28.90**
Dry recycling								
Paper and card	38.8	46.7	3.4	0.125	9303.6	0.342	0.012	4.49
Glass	19.6	23.6	1.7	0.063	4699.8	0.173	0.002	0.69
Metals (vi)	16.8	20.2	1.5	0.054	4028.4	0.148	0.140	51.22
Plastics	7.9	9.5	0.7	0.025	1894.3	0.070	0.001	0.38
Sub-Total	**83.1**	**100.0**	**7.3**	**0.267**	**19926.0**	**0.733**	**0.156**	**56.79**
Organic waste								
Food waste	100.0	100.0	5.1	0.186	13849.3	0.509	0.000	0.00
Sub-Total	**100.0**	**100.0**	**5.1**	**0.186**	**13849.3**	**0.509**	**0.000**	**0.00**
Total			**27.4**	**1.007**	**75068.5**	**2.760**	**0.235**	**85.69**

Note:

[(i)] Total waste includes waste from England, Wales, Scotland and Northern Ireland. Data obtained from DEFRA, valid in year 2016 [7].

[(ii)] Data obtained from Office for National Statistics, valid in year 2017 [51].

[(iii)] The value has been calculated by dividing the total amount of waste by number of households in the UK.

[(iv)] See Supplementary Materials: Table A.2 for the estimation of the amount of UK household waste streams based on England data. England generates 22.8 million tonnes of household waste per year, contributing to a total of 27.4 million tonnes per year of household waste in the UK. It has been assumed that each country in the UK generates the same fractions of waste stream as in England. Separately collected food waste has also been included in the total organic waste.

[(v)] The composition of residual waste has been obtained from the VALORGAS report [38] and dry recycling from DEFRA's *Digest of waste and resource statistics 2018* [7]. There is no information on the composition of organic waste stream.

[(vi)] All types of metals including WEEE, scrap metals and incineration bottom ash metals have been grouped under "Metals" in dry recycling stream.

3.5 Scenarios

The medium TDCV value of 3100 kWh/y per household (see Table 1) and annual average waste generation per household of 1007 kg/y have been taken as the basis for LCA calculation. It has been assumed that:

- Electricity is the only form of energy requirement in household (i.e. no gas or other source of energy supply) and grid electricity consists mainly of fossil fuel.
- There is sufficient electricity generated from solar PV just to satisfy the household electricity demand and neither battery storage nor external electricity supply is needed.

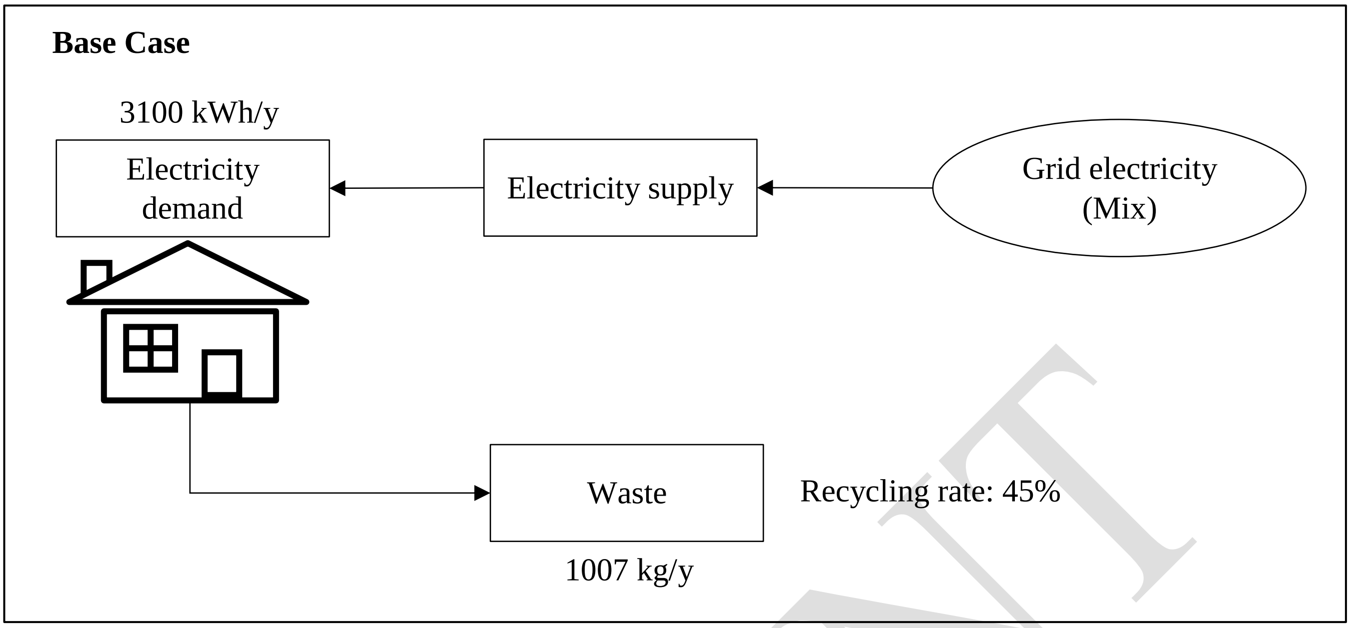
A range of scenarios with variation in energy consumption and waste generation from households has been proposed, by altering energy supply, recycling rate and resource consumption, and inclusion of resource recovery from waste strategy, detailed below.

Base case scenario (Figure 7(a)): This scenario represents the current situation in the UK households where energy and waste domains have not been considered using a systems perspective. The electricity demand in household is supplied through grid electricity. Waste is generated from household at 45% recycling rate which consists of 26.5% of dry recycling and 18.5% of separately collected food waste. The remaining 55% of residual waste is sent to landfill (29.1%) and incineration (70.9%). It has been assumed that the incineration in the present context does not include energy recovery.

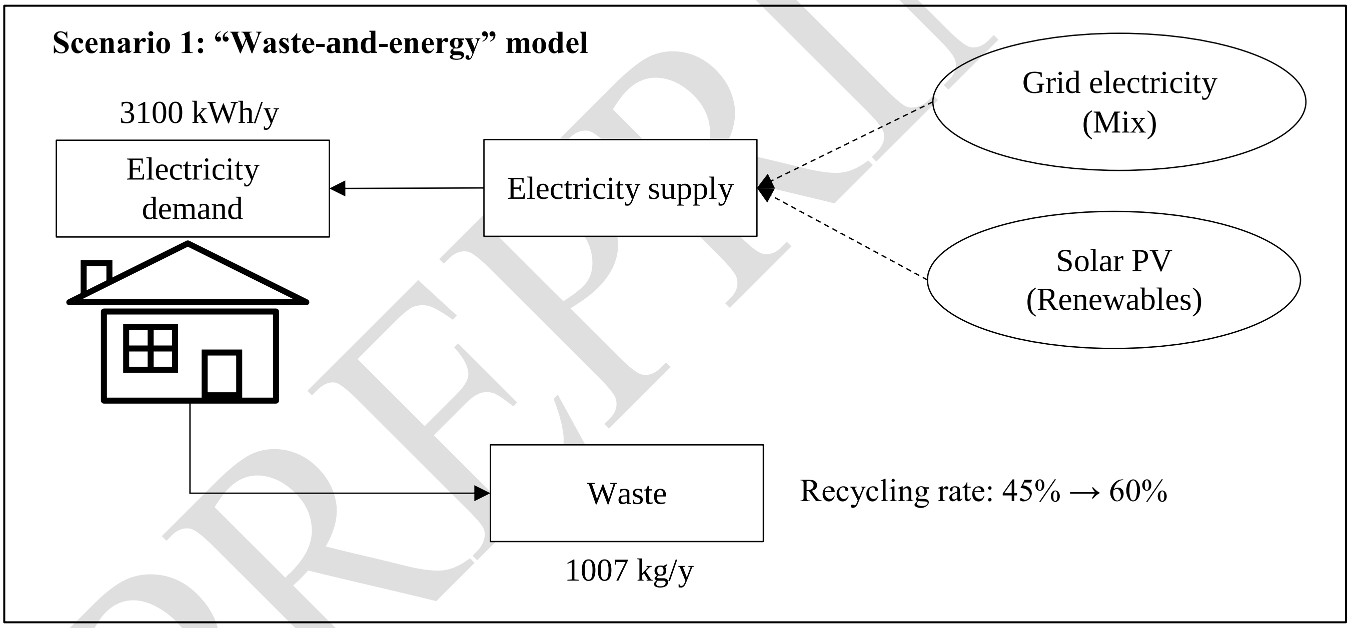
Scenario 1 (Figure 7(b)): This scenario illustrates the conventional "waste-and-energy" model where energy and waste domains in households have not been considered using a systems perspective. The improvement has been made on the respective domains independently from each other either by switching the electricity supply to residential-scale solar PV electricity while the household recycling rate remains at 45% (Scenario 1(a)); or increasing household recycling rate from 45 to 60% while using grid electricity (Scenario 1(b)); or a combination of both (Scenario 1(c)). This scenario does not take into account the concept of resource recovery from waste into energy from the household perspectives.

Scenario 2 (Figure 7(c)): This scenario presents a "waste-to-energy" model where energy and waste domains have been considered as a system from household perspective. The household electricity demand can be supplied from either grid electricity (Scenarios 2(a) and 2(b)) or residential-scale solar PV electricity (Scenarios 2(c) and 2(d)), combined with electricity generated from EfW facilities. The impact of increasing household recycling rate from 45 to 60% has also been investigated. This scenario takes into account the resource recovery from waste into energy, i.e. all residual waste has been sent to EfW facilities.

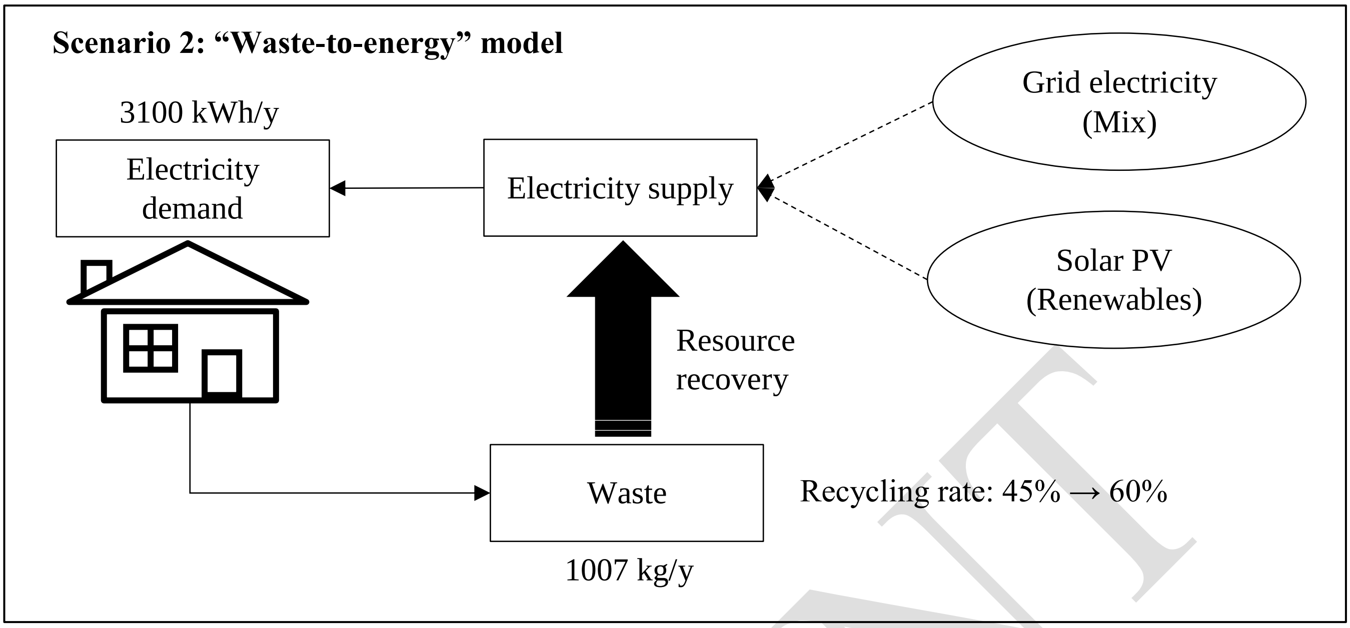
Scenario 3 (Figure 7(d)): This scenario presents a "reduced consumption" model. The energy and waste domains have not been considered using a systems perspective and resource recovery from waste into energy have not been accounted. The basis for source of electricity supply and household recycling rate for this scenario is similar to the base case scenario (grid electricity and 45% household recycling rate), except that the electricity demand has been reduced by 10% from 3100 kWh/y to 2790 kWh/y (Scenario 3(a)); and the amount of waste generation has been reduced by 10% from 1007 kg/y to 906.3 kg/y (Scenario 3(b)), in respective context.


Base Case
3100 kWh/y
Electricity demand
Electricity supply
Grid electricity (Mix)
Waste
Recycling rate: 45%
1007 kg/y

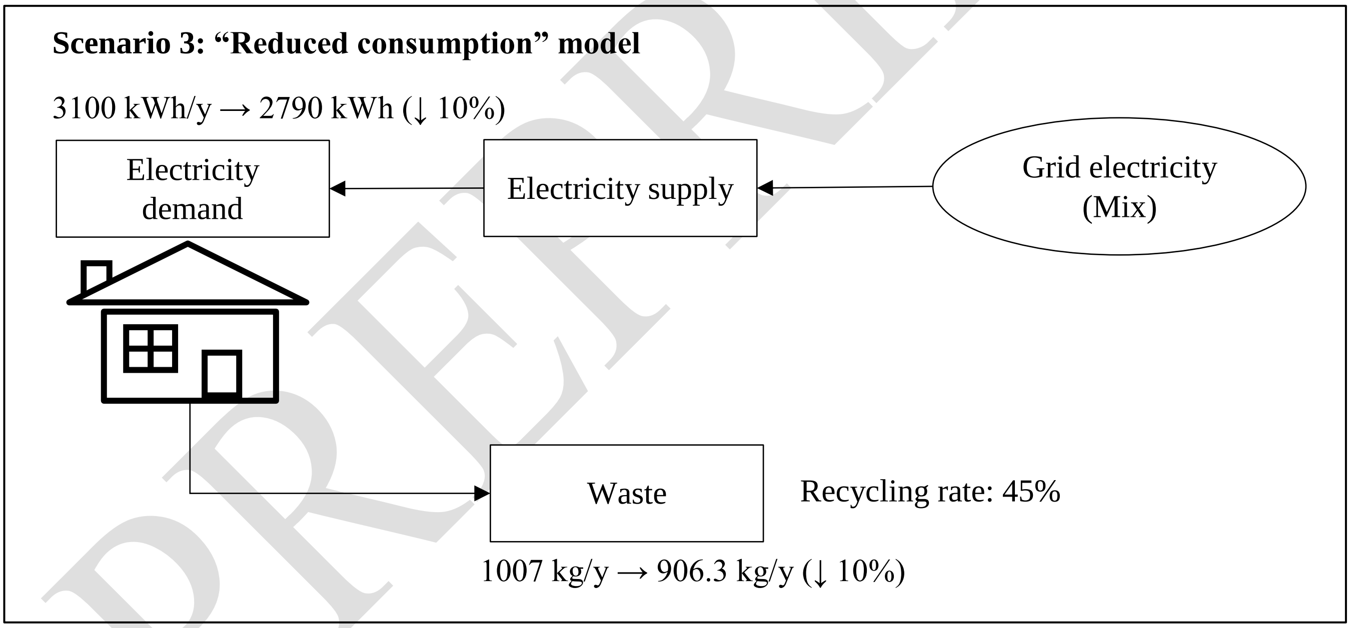
(a)


Scenario 1: "Waste-and-energy" model
3100 kWh/y
Electricity demand
Electricity supply
Grid electricity (Mix)
Solar PV (Renewables)
Waste
Recycling rate: 45% → 60%
1007 kg/y

(b)



(c)



(d)

Figure 7: Scenario analysis for enhancing household resource efficiency. (a) Base case (b) Scenario 1 – "waste-and-energy"; (c) Scenario 2 – "waste-to-energy"; (d) Scenario 3 – "reduced consumption" model.

4. Sustainability Assessment

The "waste-and-energy" model (Scenario 1), "waste-to-energy" model (Scenario 2) and "reduced consumption" model (Scenario 3), described in section 3.4, have been examined with respect to the economic (section 4.1), environmental (section 4.2) and social (section 4.3) dimensions.

4.1 Economic cost-benefit analysis

Table 6 presents the economic cost-benefit analysis for each scenario, taking into account the cost and saving on household electricity bill, income generated from incentives, council tax bill for waste management and indicative value of waste. The base case scenario shows £558 is incurred for a household with electricity consumption of 3100 kWh/y; while the cost of council tax bill for waste management and indicative value of waste have been estimated at £87.7 and £85.7 per year, respectively, associated with 1007 kg/y of waste generation per household at 45% recycling rate.

Scenario 1(a) demonstrates a potential cost saving of £703 per year with a payback period of 10.6 years if solar PV is adopted in household. This is attributed to the avoided cost of grid electricity of £558 (i.e. free electricity generated from solar PV) and an additional income of £145 per year generated from FiT (i.e. generation tariff gives £128.9 per year for 3400 kWh/y of electricity generation and £16.1 per year for 300 kWh/y of surplus electricity to be exported to the grid). Detailed calculation on solar PV related cost and income can be found in section 3.2. As there are no changes on the waste domain in this scenario, the council tax bill and indicative value of waste are identical to the base case. On the other hand, the energy domain in Scenario 1(b) is identical to the base case where grid electricity has been used, and therefore there are no savings from the energy domain. However, the increase of household recycling rate from 45 to 60% results in a net gain of £6.2 per year due to more materials recycled. Detailed calculations of council tax bill and indicative value of waste have been discussed in section 3.3. Combining the two approaches, i.e. switching to renewable solar PV for electricity generation and increasing household recycling rate, as demonstrated in Scenario 1(c) gives the highest savings/gain in both energy and waste domains.

Scenarios 2(a) and (b) examine the cost impacts if energy and waste domains are considered as a system, where part of the household electricity demand is substituted by electricity from waste while the remaining is still relying on grid electricity. If the price of electricity generated from waste is assumed to be the same as the standard price of grid electricity, i.e. 18 p/kWh, then there are no obvious benefits as compared to the base case scenario and Scenario 1. On the other hand, £513.2 per year of electricity bill reduction and additional £158.4 income generated from FiT can be obtained in Scenario 2(c), if the electricity supply is switched to solar PV. Increasing recycling rate to 60% as demonstrated in Scenario 2(d) results in less waste being sent to the EfW for energy recovery and thus increasing the consumption of free electricity from solar PV. This in turn gives higher benefits in terms of cost savings/income in the energy domain while at the same time gives higher net gain in the waste domain.

Scenario 3 presents an alternative case of reducing energy consumption and waste generation, if no changes are to be made on electricity supply and recycling rate. Intuitively, reducing 10% of electricity consumption reduces the electricity bill (excluding standing charges) by 10% compared to the base case, as indicated in Scenario 3(a). However, reducing waste generation does not lead to any reduction in the cost of council tax bills. This is because the current council tax scheme is based on a fixed rate for every household within the same band (categorised based on property value) and it is not a function of the amount of waste generation or recycling rate. A stricter penalty scheme such as the pay-as-you-throw (PAYT) scheme or a more supportive incentivised scheme such as recycling reward and deposit return schemes can be introduced to promote sustainable utilisation of resources, lower waste generation and higher recycling rate at household.

Table 6: Economic cost-benefit analysis.

Case		**Base Case**	**Scenario 1**			**Scenario 2**				**Scenario 3**	
			"Energy-and-waste" model			**"Waste-to-energy" model**				**“Reduced consumption” model**	
			a	**b**	**c**	**a**	**b**	**c**	**d**	**a**	**b**
Basis											
Specification	Unit										
Total electricity consumption per household	kWh/y	3100	3100	3100	3100	3100	3100	3100	3100	2790	3100
Total waste generation per household	kg/y	1007	1007	1007	1007	1007	1007	1007	1007	1007	906.3
Source of electricity supply		Grid	Solar PV	Grid	Solar PV	Grid + Energy from waste	Grid + Energy from waste	Solar PV + Energy from waste	Solar PV + Energy from waste	Grid	Grid
Household recycling rate	%	45	45	60	60	45	60	45	60	45	45
Contribution of energy from waste	kWh/y	0	0	0	0	248.7	180.9	248.7	180.9	0	0
Energy domain (per household basis)											
Cost of household electricity bill - grid electricity	**£/y**	**558.0**	**0.0**	**558.0**	**0.0**	**558.0**	**558.0**	**44.8**	**32.6**	**502.2**	**558.0**
- by adopting solar PV											
Saving on electricity bill (avoided cost)	£/y	0.0	558.0	0.0	558.0	0.0	0.0	513.2	525.4	0.0	0.0
Income generated from FiT, generation (income)	£/y	0.0	128.9	0.0	128.9	0.0	0.0	128.9	128.9	0.0	0.0
Income generated from FiT, export (income)	£/y	0.0	16.1	0.0	16.1	0.0	0.0	29.5	25.9	0.0	0.0
Total saving/income for 1 year, with FiT	**£/y**	**0.0**	**703.0**	**0.0**	**703.0**	**0.0**	**0.0**	**671.6**	**680.2**	**0.0**	**0.0**
Cost of PV	£	0.0	7468.0	0.0	7468.0	0.0	0.0	7468.0	7468.0	0.0	0.0
Payback period, with FiT	**years**	**-**	**10.6**	**-**	**10.6**	**-**	**-**	**11.1**	**11.0**	**-**	**-**
Payback period, without FiT	**years**	**-**	**13.4**	**-**	**13.4**	**-**	**-**	**14.6**	**14.2**	**-**	**-**
Waste domain (per household basis)											
Cost of council tax bill for waste collection and treatment (fixed scheme)	£/y	87.7	87.7	87.7	87.7	87.7	87.7	87.7	87.7	87.7	87.7
Indicative value of waste from household	£/y	85.7	85.7	93.8	93.8	85.7	93.8	85.7	93.8	85.7	85.7
Net gain	**£/y**	**−2.0**	**−2.0**	**6.2**	**6.2**	**−2.0**	**6.2**	**−2.0**	**6.2**	**−2.0**	**−2.0**

4.2 Environmental assessment

LCIA has been performed for each scenario and the results are compared in Table 7 and Figure 8.

Scenario 1(a) shows significant improvement compared to the base case where negative impacts have been obtained in all categories (except ODP), implying that employing solar PV gives the largest potential in various impact savings. Increasing the household recycling rate from 45% to 60% in Scenario 1(b) shows a smaller degree of improvement compared to Scenario 1(a). As expected, Scenario 1(c) which combines the two approaches gives the highest impact savings in all categories. Hence, the analysis from Scenario 1 suggests that switching into renewable source of energy supply such as PV as well as increasing waste recycling are beneficial in view of minimising the environmental impacts, though the adoption of renewable energy source has the potential of achieving greater reduction compared to increasing waste recycling. The extent of impact savings achieved by substituting 1 kWh of grid electricity as well as diverting 1 kg of residual waste from incineration and landfill is presented in Table 8.

Scenario 2 offers a resource recovery perspective where contribution of energy generated from waste has been accounted and thereby reducing the reliance on conventional grid electricity or solar PV electricity. Scenario 2(a) presents a case where all the residual waste is sent to EfW facilities (i.e. complete diversion of waste from landfill). This enables 248.7 kWh/y of electricity to be generated which can then substitute part of the conventional grid electricity supplied to a household. The LCIA results for Scenario 2(a) shows ADP and GWP impact savings of 29% and 25%, respectively, compared to the base case scenario. Scenario 2(b) presents a case where less residual waste is sent to EfW attributed to an increase in recycling rate to 60% compared to Scenario 2(a) at 45%, implying a substitution of 180.9 kWh per year of electricity generated from waste supplied to household. This scenario shows lower impact across all categories (except ODP) compared with Scenario 2(a), suggesting that higher recycling rate brings greater benefits than sending more waste for energy recovery. It is also interesting to examine the impact saving that is contributed by switching the electricity supply to solar PV alongside electricity generated from waste. Scenario 2(c) can be compared against 2(a) while Scenario 2(d) can be compared against 2(b). The comparison shows that significant impact savings across all categories can be achieved. Scenario 2(d) demonstrates the most promising case among all scenarios under investigation as can be seen by the largest negative impact for all categories (except ODP). Although increasing recycling rate generally increases the impact savings for ODP, however the substitution of conventional grid electricity which has a greater impact savings in ODP has been reduced in Scenarios 2(b) and 2(d).

Whilst Scenarios 1 and 2 investigate the energy and waste management using the baseline values of total energy consumption (i.e. 3100 kWh/y) and waste generation (1007 kg/y) per household, Scenario 3 presents a case where the (a) consumption of electricity per household is reduced by 10% to 2790 kWh/y and (b) waste generation per household is reduced by 10% to 906.3 kg/y. Scenario 3(a) indicates that ADP and GWP impact savings of 24% and 21% can be achieved, compared to the base case scenario, through reducing electricity consumption. On the other hand, Scenario 3(b) shows the highest impact across all categories among all the scenarios under investigation. This is because the impact savings for household waste management are mainly driven by the credits generated from re-processing of dry recycling. Although reducing the amount of waste generation inevitably reduces the credits generated from dry recycling in terms of impact savings, this should not be misinterpreted as having lower waste generation has a negative impact on the environment.

Table 7: Environmental LCIA for each scenario.

Case		**Base Case**	**Scenario 1**			**Scenario 2**				**Scenario 3**	
			"Waste-and-energy" model			**"Waste-to-energy" model**				**“Reduced consumption” model**	
			a	**b**	**c**	**a**	**b**	**c**	**d**	**a**	**b**
Basis											
Specification	*Unit*										
Total electricity consumption per household	kWh/y	3100	3100	3100	3100	3100	3100	3100	3100	2790	3100
Total waste generation per household	kg/y	1007	1007	1007	1007	1007	1007	1007	1007	1007	906.3
Source of electricity supply		Grid	Solar PV	Grid	Solar PV	Grid + Energy from waste	Grid + Energy from waste	Solar PV + Energy from waste	Solar PV + Energy from waste	Grid	Grid
Household recycling rate	%	45	45	60	60	45	60	45	60	45	45
Distance of waste transport	km	50	50	50	50	50	50	50	50	50	50
Contribution of energy from waste	kWh/y	0	0	0	0	248.7	180.9	248.7	180.9	0	0
Composition											
Residual waste	%	55.0	55.0	40.0	40.0	55.0	40.0	55.0	40.0	55.0	55.0
Dry recycling	%	26.5	26.5	34.0	34.0	26.5	34.0	26.5	34.0	26.5	26.5
Food waste (separately collected)	%	18.5	18.5	26.0	26.0	18.5	26.0	18.5	26.0	18.5	18.5
Residual waste disposal destination											
Incineration / EfW	%	70.9	70.9	70.9	70.9	100	100	100	100	70.9	70.9
Landfill	%	29.1	29.1	29.1	29.1	0	0	0	0	29.1	29.1
LCIA											
Impact category	*Unit*										

Abiotic depletion potential (ADP), element	kg Sb eq.	0.0006	0.0090	0.0002	0.0086	−0.0001	−0.0003	0.0076	0.0076	0.0005	0.0008
Abiotic depletion potential (ADP), fossil fuels	MJ	17259.0	−8954.2	13591.3	−12621.9	12239.8	9960.7	−11870.6	−14723.2	14368.9	18423.2
Global warming potential (GWP), 100 years	kg CO_2 eq.	1632.5	−694.6	1176.2	−1150.9	1227.0	883.4	−913.5	−1308.0	1374.6	1727.2
Ozone depletion potential (ODP)	kg CFC-11 eq.	0.00006	0.00000	0.0000	0.0000	−0.00004	−0.00002	−0.00009	−0.00008	0.00005	0.00006
Human toxicity potential (HTP)	kg 1,4-DB eq.	2195.1	1841.7	1175.2	821.8	3078.2	1819.1	2753.1	1486.3	2125.9	2044.8
Freshwater aquatic ecotoxicity potential (FAEP)	kg 1,4-DB eq.	17072.8	16433.7	12370.4	11731.3	23288.3	16891.8	22700.5	16290.0	16959.4	15478.9
Marine aquatic ecotoxicity potential (MAEP)	kg 1,4-DB eq.	86902502.7	84687218.6	58459915.4	56244631.3	124673862.8	85945382.9	122636286.4	83859340.8	86572695.2	78542060.0
Terrestrial ecotoxicity potential (TEP)	kg 1,4-DB eq.	9.88	−1.14	9.05	−1.97	7.16	7.07	v2.98	−3.30	8.69	10.08
Photochemical oxidant creation potential (POCP)	kg C_2H_4 eq.	0.118	−0.311	−0.0104	−0.4395	−0.010	−0.103	−0.405	−0.507	0.067	0.158
Acidification potential (AP)	kg SO_2 eq.	5.20	−5.46	3.0592	−7.6020	2.84	1.35	−6.96	−8.69	3.98	5.91
Eutrophication potential (EP)	kg PO_4^{3-} eq.	2.05	−0.22	1.4633	−0.7998	1.26	0.89	−0.82	−1.24	1.74	2.15

Note:

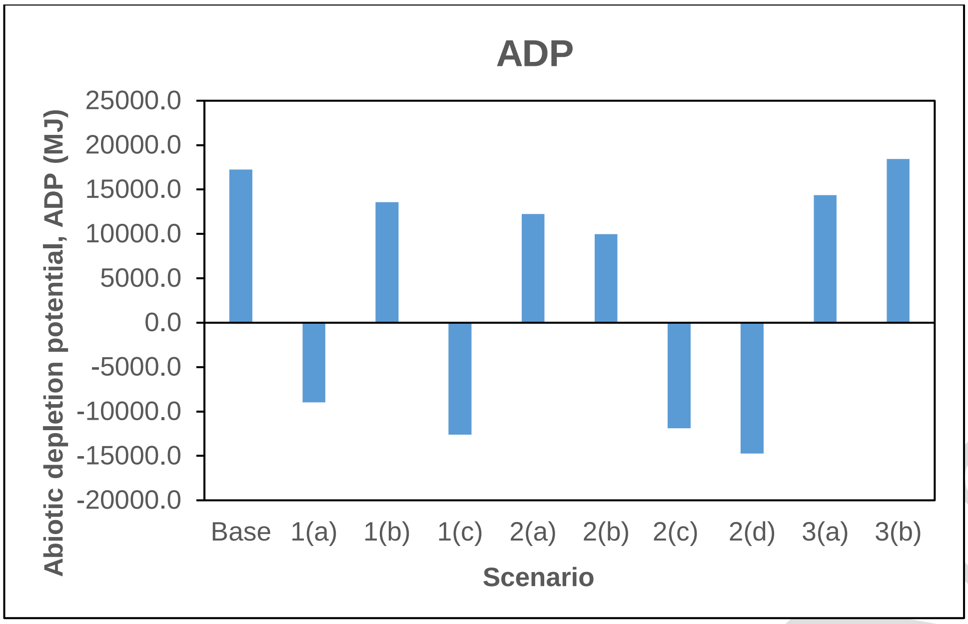
Sb: antimony; CFC: Chlorofluorocarbon; 1,4-DB: 1,4-dicholorobenzene; C_2H_4: ethane; SO_2: sulphur dioxide; PO_4^{3-}: phosphate.

More information can be found in Supplementary Materials: Appendix B.

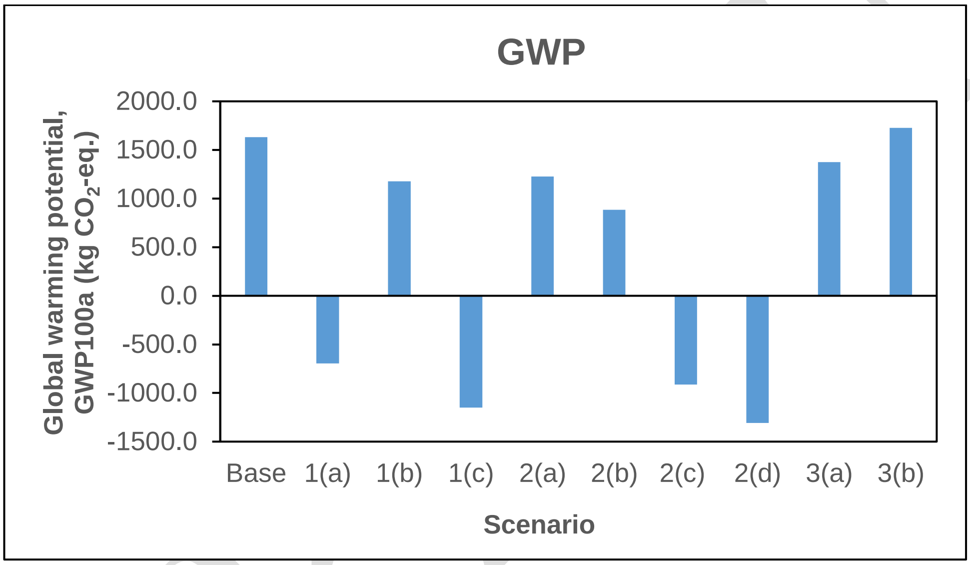
Incineration in Scenarios 1 and 3 does not include energy recovery; while 100% residual waste is sent to EfW (i.e. energy-from-waste facility or incineration with energy recovery) has been assumed in Scenario 2.

Table 8: Impact saving analysis for substitution of 1 kWh of grid electricity and recycling of 1 kg of waste.

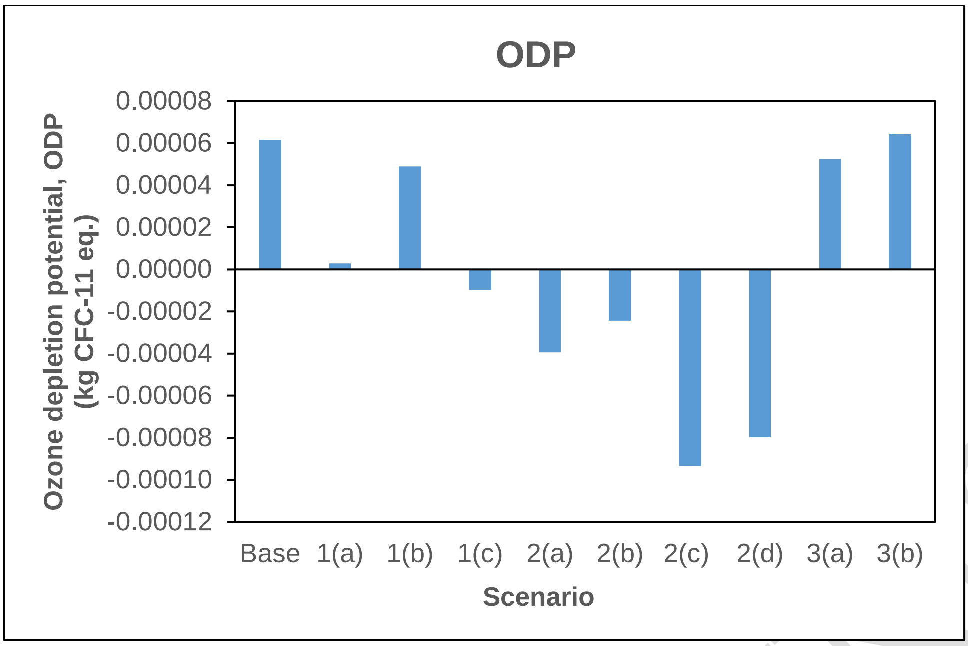
Impact category	**Unit**	**Impact saving from substituting 1 kWh of grid electricity**	**Impact saving from diverting 1 kg of residual waste from incineration and landfill**
Abiotic depletion potential (ADP), element	kg Sb eq.	−0.0000006	0.0000003
Abiotic depletion potential (ADP), fossil fuels	MJ	−9.32	0.339
Global warming potential (GWP), 100 years	kg CO_2 eq.	−0.83	0.554
Ozone depletion potential (ODP)	kg CFC-11 eq.	−0.00000003	0.0000000
Human toxicity potential (HTP)	kg 1,4-DB eq.	−0.22	4.68
Freshwater aquatic ecotoxicity potential (FAEP)	kg 1,4-DB eq.	−0.37	29.9
Marine aquatic ecotoxicity potential (MAEP)	kg 1,4-DB eq.	−1063.9	169228.9
Terrestrial ecotoxicity potential (TEP)	kg 1,4-DB eq.	−0.00383	0.0008658
Photochemical oxidant creation potential (POCP)	kg C_2H_4 eq.	−0.00017	0.0000450
Acidification potential (AP)	kg SO_2 eq.	−0.00395	0.0002106
Eutrophication potential (EP)	kg PO_4^- eq.	−0.00099	0.0009630


ADP
Abiotic depletion potential, ADP (MJ)
25000.0
20000.0
15000.0
10000.0
5000.0
0.0
-5000.0
-10000.0
-15000.0
-20000.0
Base
1(a)
1(b)
1(c)
2(a)
2(b)
2(c)
2(d)
3(a)
3(b)
Scenario

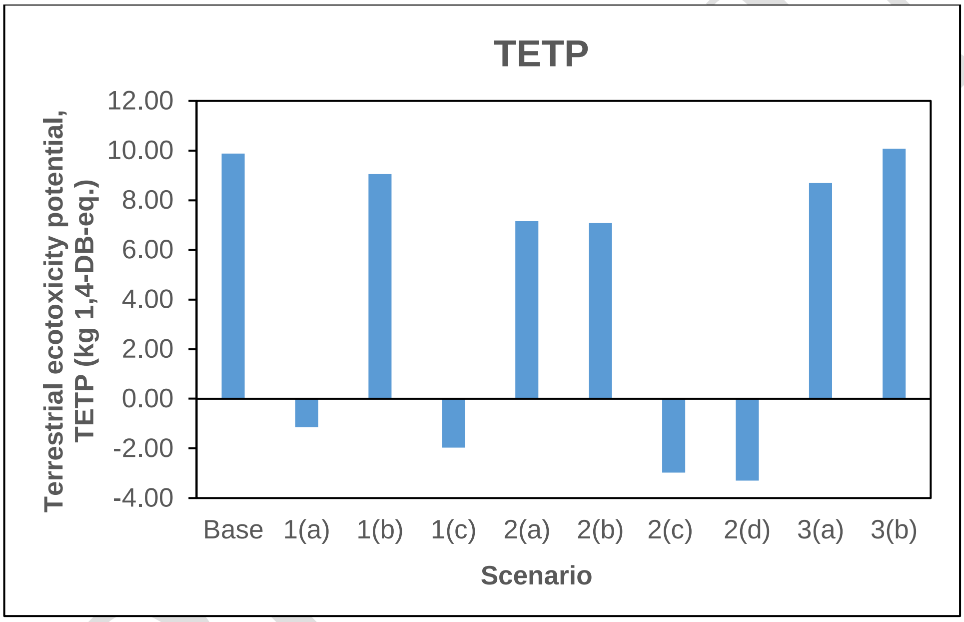
(a)


GWP
Global warming potential, GWP100a (kg CO_2-eq.)
2000.0
1500.0
1000.0
500.0
0.0
-500.0
-1000.0
-1500.0
Base
1(a)
1(b)
1(c)
2(a)
2(b)
2(c)
2(d)
3(a)
3(b)
Scenario

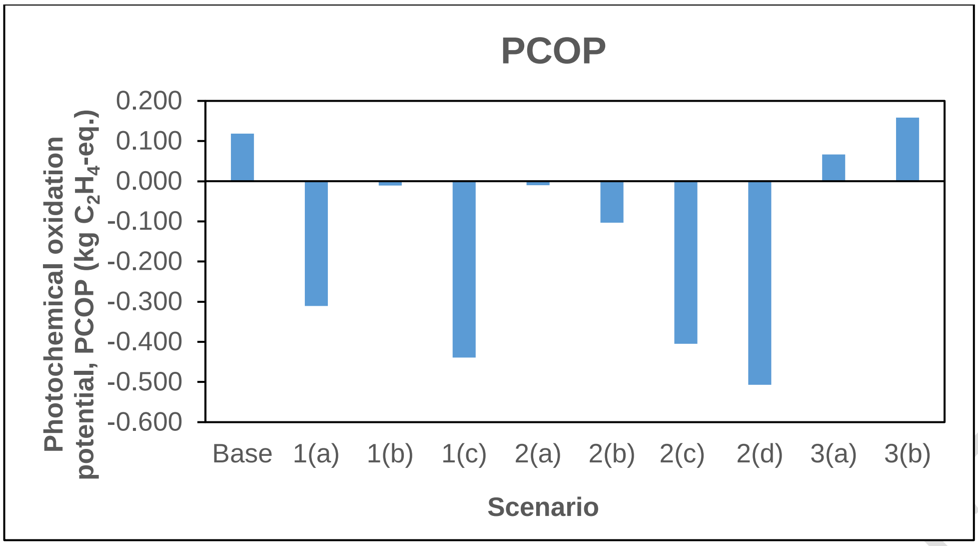
(b)


ODP
Ozone depletion potential, ODP (kg CFC-11 eq.)
0.00008
0.00006
0.00004
0.00002
0.00000
-0.00002
-0.00004
-0.00006
-0.00008
-0.00010
-0.00012
Base
1(a)
1(b)
1(c)
2(a)
2(b)
2(c)
2(d)
3(a)
3(b)
Scenario

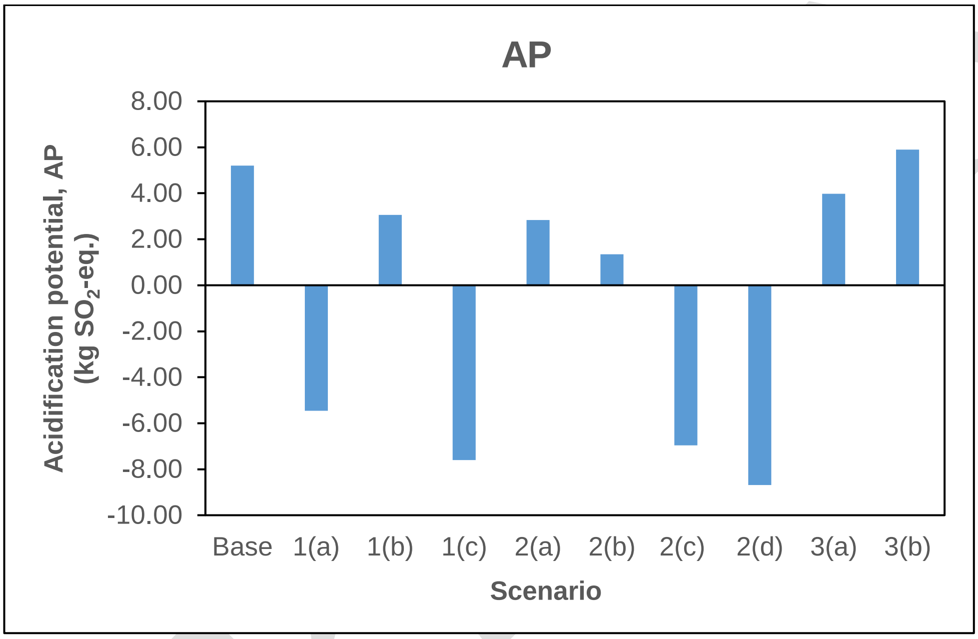
(c)


TETP
Terrestrial ecotoxicity potential, TETP (kg 1,4-DB-eq.)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
Base
1(a)
1(b)
1(c)
2(a)
2(b)
2(c)
2(d)
3(a)
3(b)
Scenario

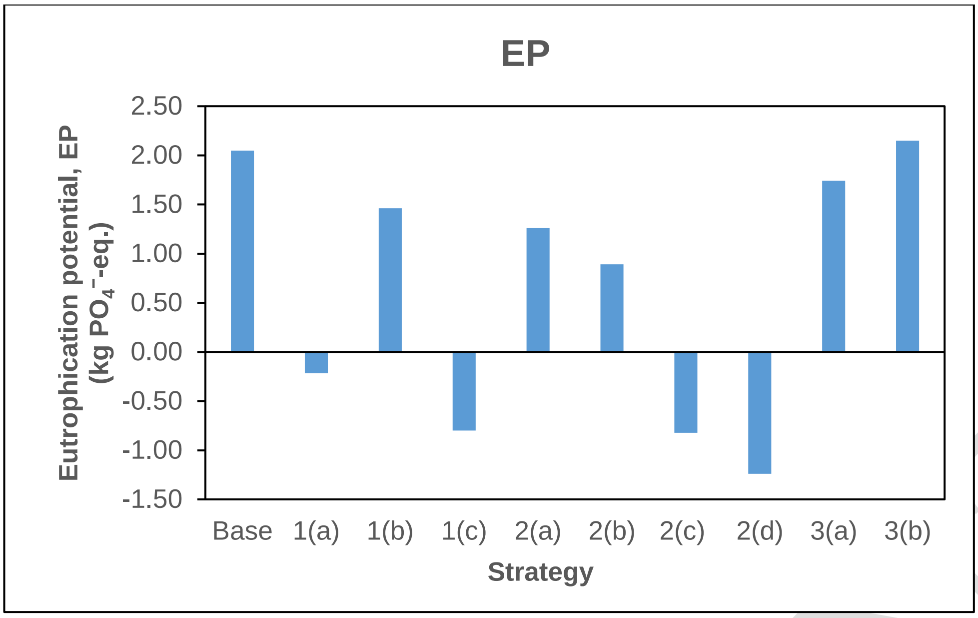
(d)


PCOP
Photochemical oxidation potential, PCOP (kg C_2H_4-eq.)
0.200
0.100
0.000
-0.100
-0.200
-0.300
-0.400
-0.500
-0.600
Base
1(a)
1(b)
1(c)
2(a)
2(b)
2(c)
2(d)
3(a)
3(b)
Scenario

(e)


AP
Acidification potential, AP (kg SO_2-eq.)
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
Base
1(a)
1(b)
1(c)
2(a)
2(b)
2(c)
2(d)
3(a)
3(b)
Scenario

(f)



(g)

Figure 8: Comparison of LCIA for each scenario.

The damage impact to human health has been analysed for each scenario and is illustrated in Figure 9. Negative damage impact (i.e. less harmful to human health) can be found in scenarios where solar PV has been adopted, i.e. Scenarios 1(a), 1(c), 2(c) and 2(d). Scenario 2(d) has achieved the lowest damage impact to human health among all scenarios attributed to the avoided impacts due to diversion from grid electricity and also credits generated from energy from waste and higher recycling rate. Almost every scenario has shown improvement in terms of reduced damage impact compared to the base case scenario apart from Scenario 3(b). The impact saving is lower because less waste materials are recycle. It should not be misinterpreted that reducing waste generation from household does not give any potential impact saving. Instead, it implies that reducing waste generation in household by 10% alone is not sufficient to make a significant improvement to lowering the damage impact to human health.

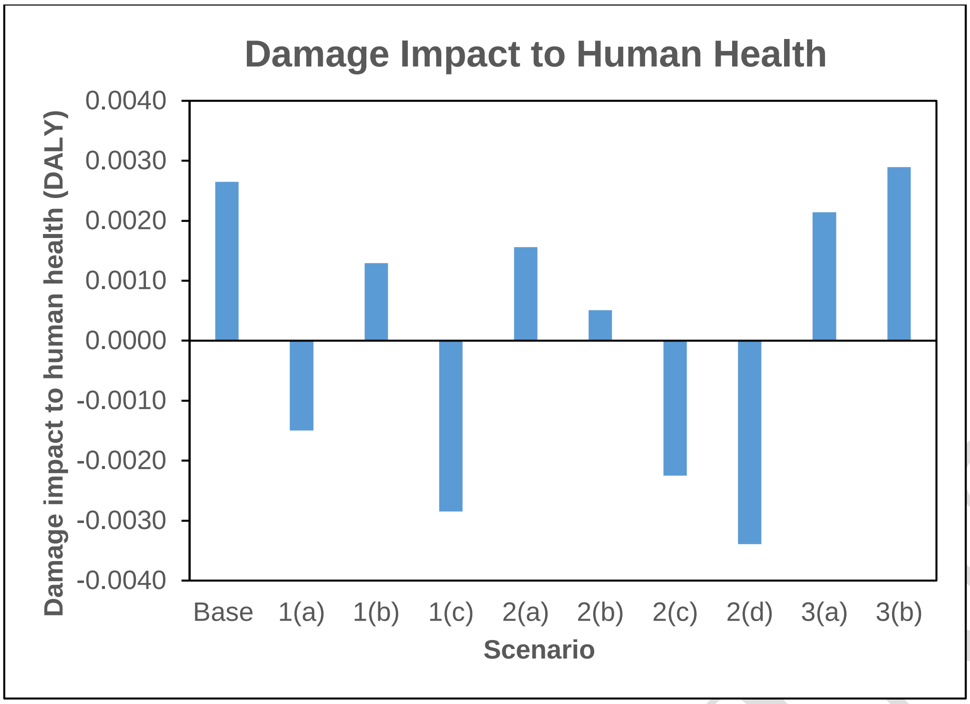


Figure 9: Damage impact to human health.

4.3 Assessment of social dimension

The social dimension has been assessed in terms of public acceptance and participation. The latest survey conducted by YouGov and ClientEarth indicated that more than 60% of the UK consumers are willing to install solar panel and energy storage device at home, provided that greater assistance from the government is given [52]. Up to September 2019, the number of solar panels installed in the UK households have reached 944,072 units (the capacity of solar PV system of less than 4 kW), with a significant rise from 5,057 units over the past 10 years since 2010 [53], which mainly attributed to the introduction of FiT in 2010. Balcombe et al. [54] discussed the motivations and barriers for adopting solar PV and other types of microgeneration systems in the UK, by considering finance, environment, security of supply, uncertainty and trust, inconvenience and impact on residence. The uptake of solar PV technologies has benefited from government subsidies and lower installation cost, however current policies do not addressed the major barrier in relation to the capital cost of PV [54]. Despite the gradual price drop in solar PV which may increase uptake of the technology, the study [54] also pointed out that it is uncertain whether consumers are willing to pay for the installation though they are convinced that solar PV can bring certain environmental benefits. Some households may be unable to install solar PV on their rooftop, for example, if their roof is unsuitable, they are in an apartment building or if they are renting. On the other hand, recycling rates are influenced by a number of factors such as deprivation level, household density, political leadership, and governance and contract [55]. More evidence is needed to further conclude the dominating factors, the impact on the public acceptance and whether a reward or penalty scheme is more appropriate in the UK context.

Overall, the paradigm shift is mainly driven by the monetary benefits through either cost reduction on energy and council tax bills or income generated from government incentives. Based on the analysis in sections 4.1 and 4.2, Scenarios 1(a), 1(c), 2(c) and 2(d) are most likely to be accepted by majority of the public because of the significant cost savings from electricity bills and income generated from FiT.

4.4 Discussions

The discussion in this section has combined the results of sustainability assessment from sections 4.1 to 4.3 and has presented in a digestible format which is useful for policy-making. The results for all impact categories have been presented for the sake of completeness. In the present context, it is more crucial to focus on ADP and GWP since these two impact categories are highly relevant to resource utilisation and emissions related to energy and waste which should be considered from the household perspective and in policy making. Hence, exhaustive discussions on other impact categories will not be included here.

Energy domain in household

For a household which demands 3100 kWh of electricity supply annually (associated with an electricity bills of £558 per year and GWP of 2579.5 kg CO_2-equivalent/year):

- Switching from grid electricity to renewable solar PV requires an additional capital investment of £7468 for a 4 kW solar panel, however resulting in a total saving/income of £703 per year with an expectation of a minimum payback period of 10.6 years if the current FiT rate is considered. From the environmental standpoint, this transformation in energy supply leads to 90% reduction in GWP or 2327.2 kg CO_2-equivalent/year of GWP impact saving. [Comparing Base Case and Scenario 1(a)]
- Introducing energy from waste into the existing household electricity supply system while substituting part of the conventional grid electricity does not offer any cost reduction, if the price of the electricity generated from waste is assumed to be the same as the price of conventional grid electricity. The GWP saving is only 8%, equivalent to 206.9 kg CO_2-equivalent/year. [Comparing Base Case and Scenario 2(a)]
- If the energy supply system in household using grid electricity remains unchanged and assuming that 10% of reduction in energy consumption can be attained, a similar percentage

of cost and GWP reduction are expected. Despite the 10% reduction in energy consumption could be a realistic and socially-acceptable approach through behavioural change, it can be seen that the cost and environmental benefits are not particularly significant. [Comparing Base Case and Scenario 3(a)]

- From the social perspective, using renewable solar PV can attain 80% reduction in damage impact to human health compared to using grid electricity. [Comparing Base Case with all scenarios adopting solar PV, i.e. Scenario 1(a), 1(c), 2(c) and 2(d)]

Waste domain in household

For a household which generates 1007 kg of waste annually at recycling rate of 45% (associated with £85.7 per year of indicative value of waste and GWP of −956.9 kg CO_2-equivalent/year):

- Increasing the recycling rate to 60% increases the value of waste by 9%, while achieving GWP savings of 46.6% to −1403.2 kg CO_2-equivalent/year. [Comparing Base Case and Scenario 1(b)]
- Substituting 8% of electricity supply using the electricity generated from residual waste increases the GWP saving by 20% to −1145.6 kg CO_2-equivalent/year. Further increasing the recycling rate to 60% leads to −1545.6 kg CO_2-equivalent/year or 61% GWP savings. [Comparing Base Case and Scenarios 2(a) and 2(b)]
- If the recycling rate in household remains unchanged and assuming that 10% of reduction in waste generation can be attained, a similar percentage of cost and GWP reduction are expected. Despite the 10% reduction in waste generation could be a realistic and socially-acceptable approach through behavioural change, it can be seen that the cost and environmental benefits are not particularly significant. [Comparing Base Case and Scenario 3(b)]

Energy and waste domains

The “waste-and-energy” model presented in this study shows the typical household perspective in energy and waste management. The economic and environmental assessment indicate that switching to solar PV for energy supply is able to bring significant benefits in terms of cost and environmental savings as discussed above. Although increasing recycling rate from 45 to 60% alone may not have much impact on cost savings due to the fixed council tax rate, it is still able to reduce GWP by 28% (i.e. 1632.5 kg CO_2-equivalent/year in Base Case to 1176.2 kg CO_2-equivalent/year in Scenario 1(b)). Switching the energy supply system to solar PV in parallel with increasing recycling rate from 45 to 60% gives the best performed scenario within the “waste-and-energy” model, giving GWP of −1150.9

kg CO_2-equivalent/year and total saving/income of £703 per year, on one household basis. This is a strategy which is achievable within short to medium term through technological transformation and behavioural change.

The "waste-to-energy" model is not a common status quo systems perspective at household but it is an emerging concept at national level. There has been question whether this is the right approach to be undertaken in the future if recovery of waste is to be regarded as the lowest priority in the waste hierarchy. The economic benefits are not as promising as the "energy-and-waste" model particularly if solar PV is not adopted. Another reason is because the same electricity price has been assumed for both grid electricity and electricity generated from waste. In spite of this, the combined approaches through switching into solar PV, increasing recycling rate from 45 to 60% and 100% of residual waste diverted into EfW for energy recovery offer significant environmental benefits, i.e. GWP of −1308 kg CO_2-equivalent/year, which stands as the best performed scenario in terms of environmental impact savings among all scenarios under consideration. This is also a practical strategy but it requires a longer time for the technological transformation and behavioural change. Although it is desirable to divert all residual waste into recycling stream, this has not been seen as a practical scenario.

"Reducing consumption" model is a special case in this study where it does not rely on any technological transformation and assuming that the current practice and perspective remains unchanged. This scenario with grid electricity and no increase in recycling rate does not show distinctive change since 10% reduction in either energy consumption or waste generation has been considered

<u>Establishing ideal "what-if" cases for the UK</u>

In the UK with 27.2 million of households, a total GWP savings of 70 million tonne CO_2-equivalent/year can be attained if all households are to adopt renewable solar PV, which avoids 84.3 TWh total grid electricity supply to all UK households. If all the materials in the residual waste stream of UK households can be diverted into dry recycling stream, this generates additional £786 million/y of revenue while avoiding GWP of 8.4 million t CO_2-equivalent/year in total at the UK level. If all residual waste stream (55% of total waste from household) is diverted into energy recovery at the UK level, this creates 6.8 TWh of additional electricity, corresponding to 5.6 million t CO_2-equivalent/year of GWP credit generation.

5. Conclusions

Households are highly resource intensive in terms of energy consumption and waste generation. A systems approach is thus needed to unlock the potential of resource recovery at household level which could address resource efficiency, fuel poverty and environmental issues more effectively at the national level. The present study complements existing research in the individual domains of household energy and waste by considering energy supply and demand, waste generation and resource recovery, trilaterally and treating them as a system. The Systems Thinking Approach to Resource Recovery (STARR) framework which consists of system analysis, scenario creation and sustainability assessment has been applied to identify potential improvements. Material flow analysis approach has unveiled the energy consumption in household with respect to appliances as well as waste generation by categories of food waste, papers and cards, glass, plastics and metals. The waste streams from household have been categorised into residual waste, dry recycling and organic waste stream and these streams have been further explored in terms of resource recovery potential. The economic value and costs of the energy and waste streams in household have been evaluated by establishing a base case to represent the implications associated with the current scenario. In this study, three models of energy and waste in households have been examined, including "waste-and-energy", "waste-to-energy" and "reduced consumption" models. These models have been further explored through different scenarios such as adoption of renewable solar PV energy supply, increasing recycling rate, integrating energy from waste into household and reducing consumption of resources and waste generation. A sustainability assessment through economic cost-benefit analysis, environmental LCA and assessment of the social dimensions was conducted to gain a holistic view of the system performance. This method informs decision-making by making the trade-offs and synergies between these dimensions clearer.

Under the current "waste-and-energy" practices, switching from conventional grid electricity to solar PV renewable electricity can result in greater environmental impact savings compared to increasing household recycling rate, though combining both approaches would certainly offer the greatest advantage. The best performing scenario in terms of lowest environmental impact demonstrated in this study combines switching to solar PV, increasing recycling rate and using electricity generated from waste, however this strategy could take a longer period to implement. Reducing consumption of resources and waste generation which merely relies on social behavioural change could be difficult in achieving significant impact if policy and motivation are not in place. In principle, the paradigm shift for the uptake of renewable technology and increasing recycling rate is normally driven by the monetary benefits either through cost reduction or income generation from government incentives.

A greater technology adoption, behavioural change and a more supportive policy instrument are essential for realising transformational changes in resource utilisation and management. A household perspective using the appropriate model for dealing with energy and waste is important for enhancing economic and environmental performance at both household and national levels. Uptake of solar PV and recycling could benefit from stronger policy support. For solar PV, this could include additional incentives for generating extra electricity which can be sold to the grid. For waste, the current fixed rate council tax means that households are charged the same rate regardless of the amount of waste thrown. The impact of introducing either a reward or penalty ("carrots or sticks") scheme for waste depends strongly on the local context and more evidence is needed before introducing such schemes. Education and community participation are important aspects in driving and promoting systems thinking in households.

Some of the practical strategies that can be introduced to the UK households based on the analysis of different models are as follows:

- If only the energy domain is considered and recognising that large magnitude of energy demand reduction (i.e. >50%) in household may not be practically achievable, then the most promising strategy is to switch household energy supply system fully into renewable solar PV electricity.
- If only the waste domain is considered and recognising that large magnitude of waste generation reduction in household (i.e. >50%) may not be practically achievable, then the most promising strategy is to promote higher recycling rate.
- If both energy and waste domains are considered, then switching into solar PV energy, increasing recycling rate and using electricity generated from waste simultaneously are the most promising strategies to achieve greater economic, environmental and social benefits.

In conclusion, examining the household energy and waste using a whole system approach enables systematic scoping of resource recovery opportunities and provide a more sustainable solution to urban planning. The transformation would not be straightforward since it involves technological transformation and behavioural change which also requires changes in policies and markets.

Acknowledgement

This work was supported by the Natural Environment Research Council (NE/R012938/1) through the UKRI/NERC Industrial Innovation Fellowship Programme, and by the Royal Academy of Engineering under the Research Fellowship scheme.

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