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The impact of climate related environmental change on the UK solid waste sector

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Abstract

This paper describes the solid waste sector in the UK and its interactions with other parts of the wider UK infrastructure system before exploring the potential effects of climate change and severe weather in the context of the UKCP09 scenarios (UKCP09, 2009). There is limited evidence for the direct effects of climate change on the UK solid waste sector. However, it is apparent that much of the disruption to the sector comes from the impact on transport infrastructure. The paper concludes that the biggest, climate-related threat to the solid waste sector, as with the UK infrastructure system generally, is flooding due to future increases in winter mean rainfall and peak rainfall events in summer and winter.

Keywords

Infrastructure planning; Waste management & disposal; Environment; Floods & floodworks;

1 Introduction

Over the last two to three decades, waste management in the industrialised world has gradually shifted from providing safe disposal of unwanted materials, often by entombing the waste in a sophisticated, engineered landfill, to recovering materials and value from that which is no longer needed through reuse, recycling, composting and energy recovery. In the UK, this shift has resulted in a 71 % reduction in the amount of biodegradable municipal waste (BMW) going to landfill since 1995. Recycling and composting have increased from almost nothing in 1995 to nearly 45 % of municipal waste treatment today and energy from wastes accounts for about a third of renewable energy generated (Defra, 2015). This has required significant investment in infrastructure as well as sustained efforts to change the attitude of industry and consumers.

In recent years, infrastructure investment and research have become a major priority in both the UK and internationally. Research has included investigations of the future of infrastructure and the resilience of infrastructure to climate change (e.g. Defra, 2011a). However, with some notable exceptions – the work of the Infrastructure Transitions Consortium (ITRC) and the recent work commissioned by Defra on improving the resilience of waste infrastructure (Winne *et al.,* 2012) - the UK solid waste sector and its associated infrastructure, has generally been omitted from these studies.

This paper will examine the research relevant to the impact of future climate change on the UK solid waste sector.

2 The solid waste sector

2.1 The current situation

According to the latest figures (Defra, 2014a, 2015; EU, 2015), the UK produced about 242 Mt of waste in 2012 of this 100 Mt was construction and demolition (C&D) wastes; 48 Mt was commercial and industrial (C&I) wastes and 26 Mt was household wastes, with the remainder consisting primarily of mining and quarrying wastes and small (<5 %) amounts of agricultural wastes and sewage sludge.

For household waste, collection is from the kerbside or a bring site (e.g. bottle and textile banks and household waste recycling centres (HWRC)). Some C&I waste is collected along with green waste from parks and gardens or with household waste from the kerbside; this forms Local Authority Collected Municipal Waste (LACMW) formerly known as municipal solid waste (MSW). LACMW collection, recycling, recovery and disposal are the responsibility of local authorities, often county councils or unitary authorities, but much of the collection and the majority of treatment are actually carried out by multinational waste management companies. The remainder of the C&I wastes are collected and disposed of by waste management companies, often using the same treatment facilities as used for LACMW.

C&D wastes are much less biologically active and are often disposed of to land, although with the target to recycle 70 % by 2020 (EU, 2008) more is being reused on construction sites.

This paper will focus on the infrastructure associated with household and C&I wastes because:

- these are the waste streams that have been the primary focus of legislation and
- the presence of large amounts of biodegradable materials make them the most complex to treat, leading to the largest treatment requirement and hence the most infrastructure.

2.2 Solid waste infrastructure

The solid waste infrastructure system now covers both waste *and* resource management as can be seen by the circular flow of wastes for use as raw materials shown in Figure 1. This system can be thought of as consisting of three subsystems – collection and transportation; treatment (which may consist of multiple steps) and final disposal.

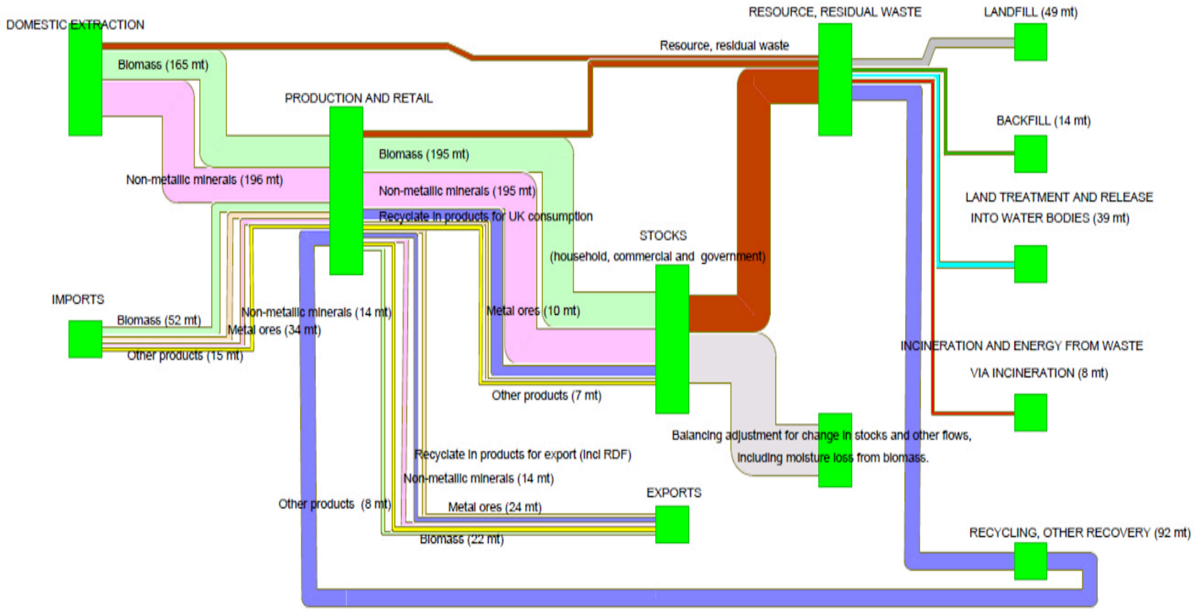

Figure 1: Sankey diagram of flow of resource in the UK, 2012, (excluding fossil fuels and energy carriers). The line at the bottom of the figure shows materials being recycled and reused. From Defra (2015) reused under the terms of the Open Government Licence.

Collection is undertaken by road vehicles. Waste is then transported to transfer stations, where it is consolidated prior to onward transport; or to material recovery facilities (MRFs) where waste (usually source segregated recyclables) is sorted prior to transportation for recycling or reprocessing. The consolidated waste is then transported by road but also rail and water to recycling or other processing facilities (e.g. anaerobic digestion (AD) or mechanical biological treatment (MBT)), thermal treatment facilities where energy is recovered from wastes for electricity or heat generation (known as energy from waste (EfW) plant or incinerators). Final disposal of material which cannot be disposed of through any other facility is entirely via landfilling.

2.3 Drivers of change in the solid waste sector

Figure 2 shows per capita English MSW arisings since the early 1990s and the apparent correlation between per capita GDP and per capita MSW arisings between 1995/6 and 2002/3. It is not clear whether a decoupling between waste generation and economic growth occurs after 2002/3 but Hall *et al.* (2012) and WRAP (2012) believe that this is the case. Even if waste generation has become partly uncoupled from economic growth, arisings are likely to increase over time (Hall *et al.,* 2012, 2015), suggesting that further infrastructure will be required.

Over the last 15 years the increases in recycling and composting and the concomitant decrease in landfilling have been driven primarily by:

- European directives – the Landfill Directive (EC, 1999) and Waste Framework Directive (EU, 2008);
- the landfill tax and landfill tax escalator and
- the 2000 and 2007 Waste Strategies (DETR, 2000 & Defra, 2007 respectively).

Research by SLR (2005) on behalf of the Chartered Institute of Wastes Management indicated that:

- a move to strategic regional planning authorities

- integration of planning across waste types, and
- compensation for communities hosting waste facilities (and other strategic infrastructure)

could significantly improve planning, remove the potential biases of some local authorities and ensure that efficiencies of scale are accessed. An ad-hoc version of this has already developed in South East England with a group of five County Councils and two unitary authorities working in partnership (Defra, 2011).

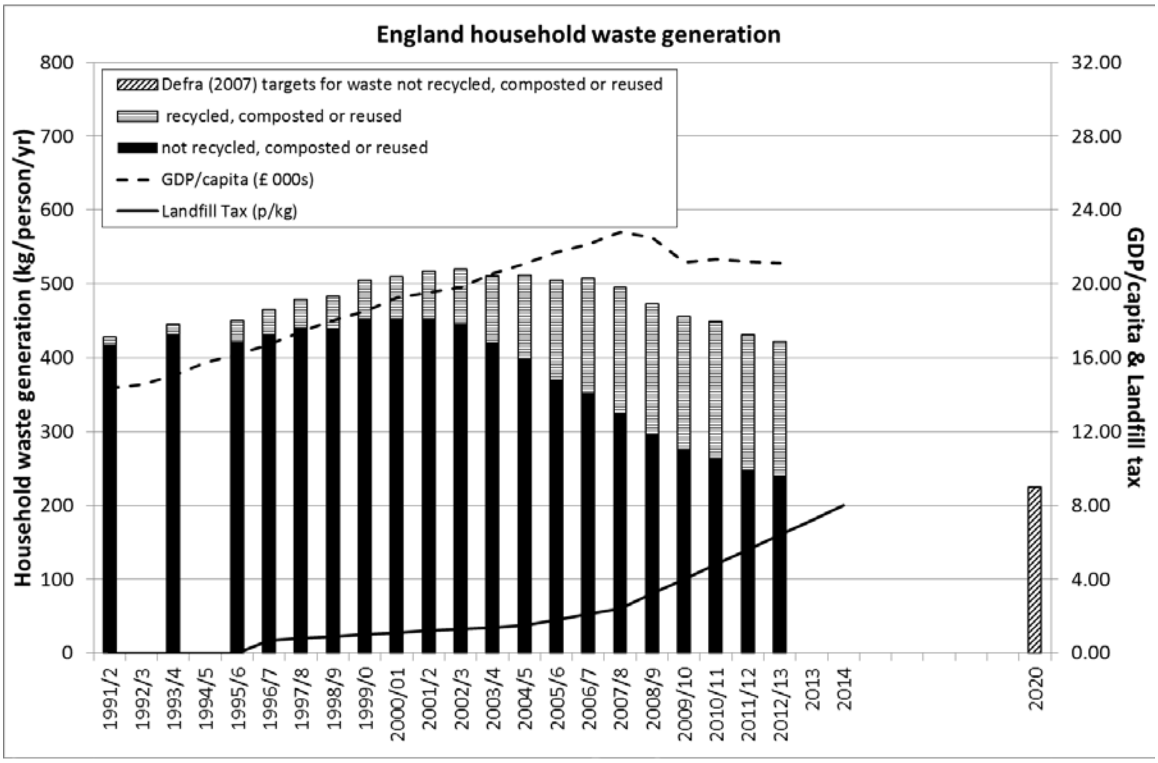

Figure 2: Per capita household waste generation and GDP for England.

3 UKCP09 climate predictions

The outcomes of the UKCP09 modelling were summarised by Jenkins *et al.* (2009). The modelling and analysis in UKCP09 is complex and a detailed discussion is beyond the scope of this report but a brief mention needs to be made of the methods. Three emissions scenarios were analysed – high, medium and low, with medium being the most likely. For each scenario and climate-related parameter (e.g. summer peak temperature, annual mean temperature, winter mean rainfall), three estimates of change were produced: the central estimate (50 % probability level); changes which are very likely to be exceeded (10 % probability level) and changes very unlikely to be exceeded (90 % probability level). Projections were averaged over 30 year time periods, labelled by their central decade. Outputs on the UKCP09 website are usually given for the 2020s; 2050s and 2080s. A typical climate projection map from UKCP09 is shown in Figure 3.

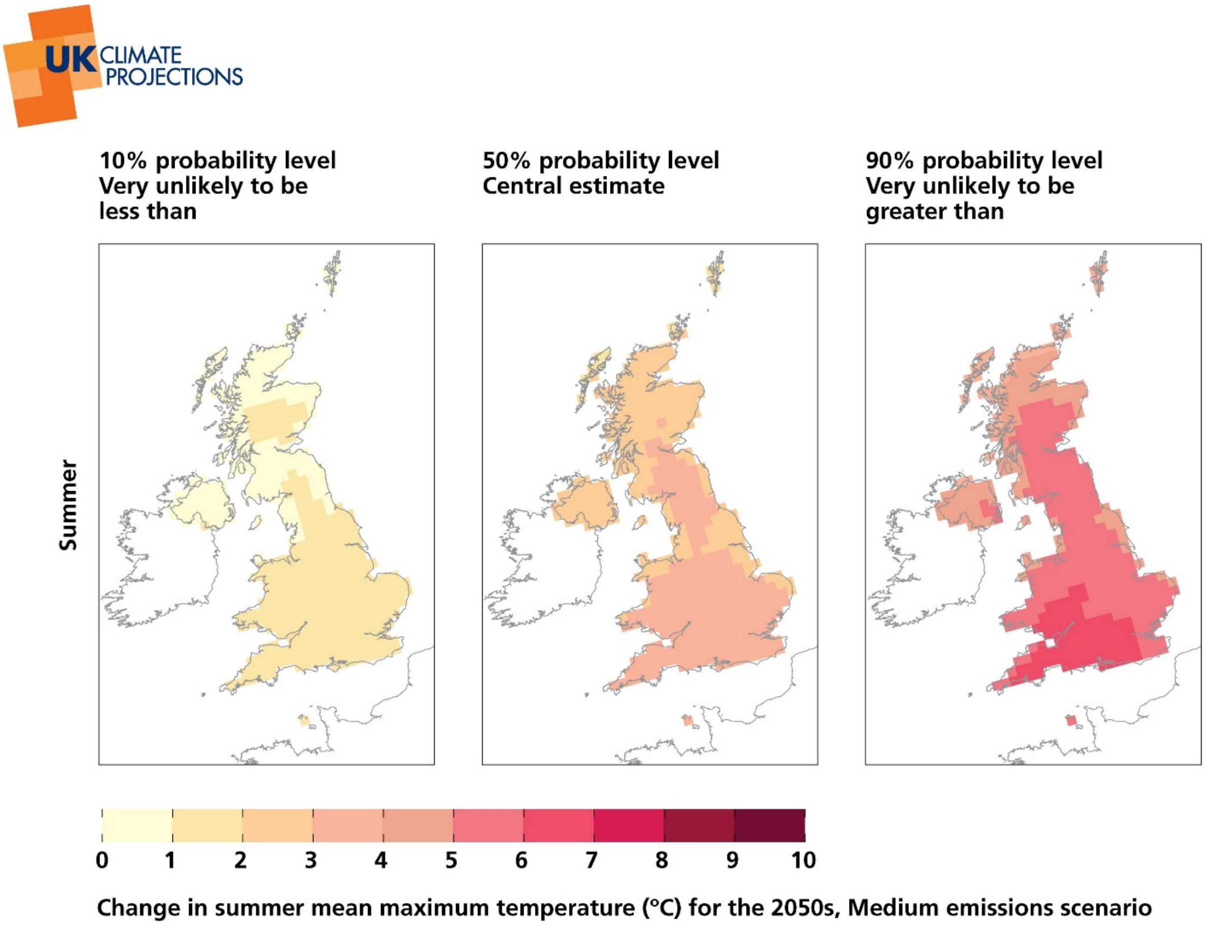

Figure 3: Typical presentation of projected climate data. Those shown are for change in summer mean maximum temperature for the medium emissions scenario in the 2050s. © UK Climate Projections 2009.

The predicted changes (relative to the 1961-1990 baseline) most relevant to the waste sector under the medium emissions scenario are shown in Table 1. In addition, sea levels are expected to rise by 11 to 26 cm by the 2050s relative to the 1990 baseline (ASC, 2014).

Table 1: Showing the climate variable and the changes relative to the 1961-1990 baseline predicted in UKCP09.

	Data from UKCP09 (2009) for the medium emissions scenario at 50 % probability level. All are relative to 1961-1990 baseline and are averaged over a 30 year period centred on the named decade (i.e. 2020s is average of 2010 to 2039).		
Climate Variable	2020s	2050s	2080s
Winter Mean temperature	1 to 2 °C	1 to 2 °C in the North 2 to 3 °C in the South	2 to 3 °C except 3 to 4 °C E. Anglia & S.
Summer Mean temperature	1 to 2 °C	2 to 3 °C	3 to 4 °C
Winter mean maximum temperature	1 to 2 °C	2 to 3 °C except 1 to 2 °C in the West	2 to 3 °C
Summer mean maximum temperature	1 to 2 °C most of UK	2 to 3 °C Scot., N.I., N. Wales 3 to 4 °C Central & S. Eng.	4 to 5 °C except 5 to 6 °C central S. Eng. 3 to 4 °C far North
Warmest day of summer	0 to 2 °C	2 to 4 °C	2 to 4 °C Central & S. Eng. 4 to 6 °C N. Eng. & Scot.
Annual mean precipitation	0 to 10 %	0 to 10 % except -10 to 0 % North, S. Coast & W. Wales	0 to 10 % except -10 to 0 % North, S. Coast & W. Wales
Winter mean precipitation	0 to 10 %	10 to 20 % except on high ground	10 to 20 % largely 20 to 30 % some areas
Summer mean precipitation	-10 to 0 % except	-20 to -10 % except	-30 to -20 % except

	-20 to -10 % S. Coast & far West	-30 to -20 % S. Coast & far West	-40 to -30 % S. Coast & far West

4 Potential impacts of climate change

Climate change and weather will impact on the solid waste sector directly through disruption to the solid waste infrastructure and indirectly through disruption to other infrastructure (e.g. failure of the electricity grid; disruption of transportation routes or failure of water supplies). According to the Adaptation Sub-Committee (ASC, 2014), "increased flood risk is the greatest threat to the UK from climate change". The ASC's analysis summarised in Table 2 shows that flooding will similarly be the biggest threat to the waste sector, with temperature increases likely to also be problematic for the industry. The effects of different climate factors are outlined in table 2, along with the ASC's confidence in the occurrence of each factor.

Table 2: Effects on solid waste management and infrastructure due to climate change and the confidence in the climate factor.

Climate Factor	Confidence in climate factor (ASC, 2014)	Effect
Increased winter rainfall and/or increased peak winter rainfall	High	Increased waste arisings due to flood events.
		Disruption to transport network due to flooding.
		Flooding of landfill sites leading to increased risk of groundwater and/or surface water contamination and additional treatment of leachate.
		Flooding of waste facilities leading to ground and /or surface water contamination.
		Disruption of energy supply leading to breaks in waste treatment services.
Increased frequency of winter storms	Low	Increased storm damage to waste facilities.
		Disruption to transport network.
Sea level rise and increases in storm surge	High (sea level rise) Low (UK storm surge)	Exposure of historic coastal landfill sites leading to pollution events.
		Disruption to marine transportation of wastes.
Higher summer temperatures	High	Increased incidents of landfill fires.
		Increased incidents of fires in other waste facilities.
		More frequent waste collection required to reduce problems with vermin and odour.
		Disruption to transport network (e.g. rail buckling, highway damage).
Increased frequency of periods of drought	Low	Shortage of water for AD and composting.
		Disruption to river and/or canal transportation due to reduced water levels.
		Reduced river levels may lead to reduction in water available for cooling EfW plant.

Changes in climate will affect the waste infrastructure through both changes in extreme conditions (e.g. the hottest summers and wettest winters) and shifts in the mean (e.g. average summer temperatures and mean seasonal rainfall). The effects of climate change are different across the UK with the biggest changes occurring in central and southern England where about 60 % of the population is concentrated. According to Winne *et al.* (2012), 68 % of all English “major waste sites” and 65 % of planned waste sites are located in this area.

Recent changes in legislation (e.g. the requirement in the Landfill Directive that all waste is pretreated prior to landfilling (EC, 1999)) have led to a move away from spatially dispersed facilities (thousands of landfills) towards a limited number of specialised facilities (e.g. 87 UK incinerators). This has resulted in increased system vulnerability due to both the limited number of facilities and the increased requirement for transportation.

UKCP09 shows increases in winter mean rainfall and peak winter rainfall, both of which are likely to lead to increasing incidents of flooding. The 2012 UK Climate Change Risk Assessment (Ramsbottom *et al.,* 2012) states that the number of properties in England and Wales with an annual flood risk of 1:75 (1.3 %) is projected to rise from 560 000 to between 800 000 and 2.1 million by the 2050s and to between 1.0 and 2.9 million by the 2080s. Ramsbottom *et al.* (2012) also state that not only are more people likely to be affected by flooding but that the frequency of flooding is also projected to increase. Extreme wind events (possibly coupled with heavy rains) can lead to coastal flooding due to storm surges (e.g. December 2013 storm surge in the North Sea), although according to the Adaptation Sub-Committee (ASC, 2014), neither the magnitude nor frequency of storm surges are likely to increase. However increases in population may increase the number of properties and people affected by an event.

Flooding is likely to generate high levels of extraordinary waste arisings. For example, according to government figures (gov.uk, 2014), 7800 houses and 3000 businesses were flooded in the winter of 2013/14 all of which will have produced waste. While the absolute quantities of waste are not large, they may significantly increase the waste arisings in a given area – the average household produces about a tonne of waste a year, of which about 30 % is recycled. Although no figures are available, it is not unreasonable to assume that flooding would generate at least 250 kg of extra waste per household (water damaged kitchen units, carpets, plasterboard, white goods etc.), of which none is likely to be recycled. This extraordinary waste is likely to require landfilling – the more modern, process based infrastructure (e.g. EfW, MRF, AD) is generally rate or capacity limited and is therefore unlikely to be able to deal with very high levels of waste produced in a short time without a mechanism for storage. Landfill could be used as a temporary store to smooth waste flow but this would require landfills to be publicly owned or to have a means of income from this holding function. Flooding may also result in excessive runoff from capped landfills or excessive leachate generation, although the landfill itself will have a buffering capacity that can be assessed using recently developed tools on liquid storage and flow (White *et al*., 2011). In extreme cases, landfill sites may flood, although Laner *et al.* (2009) concluded that the environmental risks were relatively small. Coastal erosion is likely to be increased during storm events which will make coastal landfills more vulnerable. For modern landfills, there should be plenty of warning of this but for older, poorly documented sites, the first warning may be the appearance of waste on beaches (NERC, 2008, Cooper *et al.,* 2012).

Increases in the mean temperature will increase odour, dust and vermin in waste processing facilities leading to difficult working conditions. Increased mean and peak temperatures are likely to lead to an increased frequency of fires in refuse collection vehicles (RCVs), MRFs, stockpiles of recyclables awaiting reprocessing (e.g. paper, plastics, tyres) and landfills. There were 59 fires at recycling facilities in the UK in 2012 (Ryan, 2012) and insurers say figures are under-reported (Hudson & Fulford, 2013). There are around 300 landfill fires in the UK each year (Foss-Smith, 2010). A reduction in summer rainfall may cause problems for composting and AD plant, both of which require water, as well as limiting the availability of water for cooling in EfW plant (Sinton & Greenwood, 2009). Changes in rainfall may also affect landfill leachate balances, degradation and gassing and have implications for leachate management system loadings that can be assessed as above.

The ways these changes are likely to affect the waste sector are summarised in Tables 2 and 3.

Table 3: Summary of potential impacts on the solid waste sector due to climate change.

Climate Impact	Waste Subsystem	Effects
Mean temperature rise	Collection	Increased collection rate for putrescible wastes. Increased fire risk in collection vehicles[1].
	MRF	Increased fire risk in sorting lines and in recyclate stockpiles[1, 2, 3]. Increased problems of odour and vermin.
	Reprocessor	Increased fire risk in recyclate stockpiles[1, 2, 3].
	Landfill	Increased risk of landfill fires[1, 4]. Increased problems of odour and vermin. Increased risk of desiccation and cracking of clay liners and caps with associated pollution risks[5].
Peak daily temperature rise	Collection	Increased fire risk in collection vehicles[1]. Increased risk of disruption due to road damage[6].
	Transport	Increased risk of disruption due to road damage and rail buckling[6].
	MRF	Increased fire risk in sorting lines and in recyclate stockpiles[1, 2, 3].
	Reprocessor	Increased fire risk in recyclate stockpiles[1, 2, 3].
Mean and peak daily winter rainfall rise.	Collection	Increased risk of disruption due to flooding[6, 7].
	Transport	Increased risk of disruption due to flooding[6, 7].
	Treatment	Increased risk of disruption of waste supply due to flooding; may lead to plant shut downs and hence reductions in energy supply.
	Landfill	Increased flood risk requires use of landfill to deal with increased waste generation rates. Extreme rainfall leading to increased runoff. Increased risk of flooding of landfill leading to pollution events[8, 9].
	EfW	May be limitations on the extraction of river water for cooling[10].
Mean summer rainfall reduction	Composting and AD	Scarcity of water required for degradation. Plant may need to stop taking waste.
	River transport	Increased risk of disruption due to low water levels.
Coastal processes	Landfill	Increased risk of erosion could lead to exposure of waste at coastal landfills[11].
Extreme wind events	Landfill	Increased risk of flooding requires use of landfill to deal with peak waste generation rates.
Wetter winters and drier summers	Transport	Increased risk of damage to road and rail due to increased rates of embankment failure and subsidence[12].

[1] Moqbel *et al.* (2010); [2] Ryan, (2012); [3] Hudson& Fulford (2013); [4] Foss-Smith (2010); [5] Sinnathamby *et al.* (2013); [6] Ramsbottom *et al.* (2012); [7] Thornes *et al.* (2012) ; [8] Laner *et al.* (2009); [9] Neuhold & Nachtnabel (2011); [10] Sinton & Greenwood (2009); [11] NERC (2008) ; [12] Pritchard *et al.* (2014);

4.1 Key Vulnerabilities

The vulnerabilities of each of the three solid waste infrastructure subsystems are different and so will be discussed separately.

4.1.1 Collection and transportation

As most waste is dealt with locally, collection and transportation involves primarily the road network. Some large sites and co-combustion sites (those which burn waste along with other materials to generate electricity (e.g. coal fired power stations) or heat (e.g. cement kilns) are located by railways or rivers (e.g. Rainham landfill and Belvedere EfW, London's largest MSW treatment plant, are both dependent on the Thames for the delivery of waste). In the future, the availability of low energy transport options may be a requirement for siting of new plant; Winne *et al.*(2012) have suggested that this is already happening.

In general, collection and transportation are likely to be affected by any climate related event that affects roads (e.g. flooding; high temperatures; snow and ice and high winds), railways (e.g. flooding; high temperatures and snow and ice), canals (becoming un-navigable during floods or prolonged drought) and major rivers (e.g. high water levels and flows due to extreme rainfall, floods, meltwater or storm surge; low levels due to prolonged dry periods). The combination of reduced summer rainfall and increased winter rainfall is likely to lead to greater road and rail disruption due to increasing subsidence and embankment failure (Pritchard *et al.,* 2014).

It should be noted that the issues described above are far more likely to affect the transportation of waste rather than collection, which tends to occur locally. Any event disrupting local collection is likely also to cause disruption to the waste generating processes (e.g. local flooding may also lead to local evacuation, hence households are producing no waste, at least until the floodwaters have subsided).

A percentage of UK waste is transported overseas. This is typically in the form of refuse derived fuel (RDF) being shipped to Europe for use in EfW plant due to over-capacity in Europe (Date, 2013 & 2014), although Defra are encouraging the development of more domestic capacity (Defra, 2014b); and shipment of recyclables to China and elsewhere (WRAP,2011). This export may be affected by all the issues described above. Additionally, shipping will be directly affected by flooding, high winds, storm surges etc. in the receiving port, sea level rise and delays due to increased frequency and magnitude of storm events in the shipping lanes. Winne *et al.* (2012) go into somewhat greater detail of possible disruptions in China and elsewhere as a result of climate change.

4.1.2 Treatment

All treatment facilities (e.g. MRFs, AD, composting facilities, mechanical biological treatment (MBT) & mechanical heat treatment (MHT) plant and EfW) have the potential to be affected by the climate related events outlined above. All of these facilities require that the incoming wastes are stored inside, usually with a restriction on the maximum length of time material can be retained prior to treatment. On-site storage in an enclosed space may be affected by increased summer temperatures giving rise to issues with vermin, dust, odour and pathogens all of which are likely to impact primarily those who work in the facilities. According to Winne *et al.* (2012), over two thirds of all major waste sites in England are located in southern and mid England, which are likely to see a summer mean temperature rise of between 1 and 2 °C by the 2020s. By the 2050s, all major English facilities are likely to see mean summer temperature increases of 2 to 4 °C. Flooding will directly affect treatment facilities either by making it difficult for staff to access them (which is also likely to affect delivery of waste to the facility); increased demand due to flood-generated waste in the facility catchment area; or by direct flooding of the facility itself. By 2050 all UKCP09 scenarios show an increase of 10 – 20 % in winter precipitation, at least for central and southern England, where much of the waste infrastructure is located. Flooding of waste facilities in flood plains and in coastal areas may also increase the risk of contamination of surface and groundwater (Wilby *et al.*, 2005).

4.1.3 Final disposal

Final disposal is to landfill. Bebb & Kersey (2003) suggested that flooding and increases in precipitation may disrupt leachate and gas collection. Increases in summer temperature and reductions in summer precipitation may also lead to increased risk of landfill fires due to wastes being drier when deposited and generally warmer (Moqbel *et al.*, 2010). As for other waste facilities, flooding of operational landfill may increase the risk of pollution incidents. Laner *et al.* (2009) examined the risk of flooding of landfills in Austria together with the potential emissions during flooding assuming “complete landfill leaching and erosion” and found that whilst many landfills were vulnerable to flooding, the environmental risk was relatively small.

The Environment Agency has assessed the risk to groundwater of existing (open and closed) landfills (EA, 2010a & 2010b) but it is not clear whether the additional risks posed by climate change have been taken into account.

Coastal erosion will increase with sea level rise in some areas, leading to an increased risk of exposure of waste in coastal landfill sites (Cooper *et al.,* 2012 and Chancerel, 2008) as occurred on the south coast in 2008 (NERC, 2008).

Increased summer temperatures may damage landfill caps or exposed portions of clay liners by desiccating the clay cover leading to cracks appearing, allowing greater water ingress and potentially leading to a breach of permitting conditions unless the leachate pumping system is able to deal with the increased volume.

A potential issue with the long term storage of wastes in landfill is that the duration over which waste must be stored prior to reaching a condition of equilibrium with its environment (the “final storage” condition) is very much longer than the period modelled in UKCP09 (Hall *et al*., 2004).

4.2 Cross sector interactions

The primary interactions between the solid waste sector and other infrastructures have been investigated in ITRC (Hall *et al.,* 2012, 2014; Tran *et al.,* 2014) and are detailed below.

4.2.1 Transport

The majority of waste is moved by road, with RCVs collecting from households and businesses and haulage vehicles moving consolidated wastes and treated recyclables for recovery or disposal. It is likely that periods of disruption to collection (e.g. snow, floods, fuel shortages, etc.) would create a backlog of waste that treatment plants would struggle to clear, hence a requirement for landfill. This will involve mainly the road network, although as already mentioned waste is also transported by rail and river

4.2.2 Energy

The solid waste infrastructure depends on the energy sector. For example, the failure of electricity would disrupt most waste treatment services (e.g. leachate and gas extraction from landfills; operation of MBTs, MRFs and EfW), and disruption to liquid fuel supplies would affect transportation and collection of wastes as well as site operations at most waste facilities, necessitating the storage or stockpiling of waste or disposal to landfill. It could also prevent leachate pumping in landfills, increasing the risk of pollution events. Energy generated from waste forms almost a third of renewable energy (DECC, 2013) and about 3 % of the UK’s electricity. However, energy from waste may become more important in the drive to increase the use of renewable fuels, in which case disruption to waste infrastructure could affect the UK’s generating capacity more significantly.

4.2.3 Water

Some waste treatment facilities require a supply of water, e.g. composting and AD, in which water is used to aid biodegradation. Failure of the water supply to such facilities would lead to cessation or a reduction of treatment capacity and the need to dispose of the waste by alternative means or to store it.

4.2.4 Waste water

Landfill produces large amounts of potentially polluting leachate which is typically treated on site before being disposed of through the wastewater network or direct to surface water. If local wastewater treatment facilities failed, the leachate could be tankered to alternative plants (although there would be costs associated with this) or treated to a higher standard, so the impact on landfilling would be minimal. Changing waste streams may make the leachate impossible to treat with the current biological systems. Sewage AD plant could be used to process biodegradable municipal waste (BMW). This would significantly increase both the plant throughput and gas yields and would necessitate plant upgrades and probably upgrading the transport network, but at present seems not to be cost effective owing to the need to macerate the MSW first. It may be that AD systems suitable for solid wastes could be developed on sewage treatment sites which could than treat MSW without pre-treatment, as well as sewage, farm wastes and other material suitable for AD.

4.2.5 *ICT*

It is possible that there will be increased reliance on ICT in the solid waste sector e.g. smart bins dynamically modifying logistics of collection rounds. However, the adoption of a default sequence would minimise the effect of a loss of ICT services.

4.2.6 *Flood and coastal erosion management*

For there to be no future impact of flooding on the solid waste sector, flood defences and flood resistance of property would need to be modified such that there are fewer waste-generating flood events than in the 1990s (increased moves away from landfill as a means of final disposal has made the system less resilient to these events and this trend will continue). Siting of future waste infrastructure away from flood risk zones should reduce the risks of loss of service. Coastal erosion has the potential to expose coastal landfills with the risk of uncontrolled pollution incidents (NERC, 2008). Coastal erosion may also affect other waste infrastructure, unless it is sited away from vulnerable coasts.

5 Knowledge gaps and research priorities

There has been very little investigation into the effects of climate change on the solid waste sector or into the costs of adapting the sector to change including increasing resilience. The National Adaptation Programme (Defra, 2013) makes no mention of solid waste infrastructure. The UK government report on climate resilient infrastructure (Defra, 2011a) makes little mention of the solid waste sector other than to observe its non-consideration and to commission the research that resulted in the AEA Technology report on resilience of waste infrastructure (Winne *et al.*, 2012). The 2012 Climate Change Risk Assessment (CCRA) (Defra, 2012a) did not include any assessment of solid waste infrastructure but stated that it "was not identified as a priority area as part of this first CCRA". Winne *et al.* (2012) recommended that "the waste sector should be included within future cross-Government work exploring interdependencies and climate resilience". The authors are contributing on solid waste to the infrastructure section of the second CCRA but as there is no funding for new research, it is clear that the gaps in understanding identified here will likely also be present in the second CCRA.

Winne *et al*. (2012) identified the potential costs of adapting to climate change as a serious concern to waste stakeholders. However there were no details of costs in their report and they also stated that "resilience measures do not necessarily imply increased costs". Bebb & Kersey (2003) discussed costs but did not quantify them. Further research is needed to gain a better understanding of risks to the solid waste infrastructure is needed as well as estimates of the costs for any necessary improvements to resilience.

For future infrastructure, it is clear that climate change will be taken into account during the planning stages and is likely to influence the siting of waste facilities and if necessary, stipulate means for the mitigation of climate related hazards e.g. bunds to reduce flood risk (Winne *et al.,* 2012). This may have cost implications, given the number of planned waste infrastructure sites identified by Winne *et al.* (2012) as being in areas most affected by climate change.

According to the Environment Agency (EA, 2009), 5.2 million homes in the UK are at risk of flooding. Climate change will lead to more flooding unless there are very significant investments in flood defences. Without modifications to the UK housing stock, flooding will lead to increased waste arisings locally, along with their associated costs for treatment and disposal. The costs associated with the latter tend to get lost in the overall costs of clean-up. There is a need for further research on the effects of flooding on both the magnitude of flood related waste arisings and their composition which is likely to differ significantly from the normal waste stream.

Disruption of the UK transport network will affect both the collection and transportation of wastes and incidences of disruption will increase (Thomas *et al.,* 2012) but further research is needed to establish the costs to and effects on the waste sector.

The Environment Agency has a document listing flood risks to regulated waste sites but this is not publicly available so it is unclear whether it lists risks to closed landfill sites, which may number as many as 25000 according to some sources (ESI, 2009). Many of these landfills are old and likely to be largely inert; however, the EA regulates 2600 of which 2100 have closed in recent times, many of which will still be chemically and biologically active and hence capable of polluting the surrounding environment. It may be that research is needed to identify those sites at greatest risk.

Disruptions to the supply of wastes to energy generating waste facilities (e.g. AD and EfW plant) could lead to a cessation of energy generation and hence a reduction of supply to the grid but again further research is needed to quantify the probable impact on UK energy supply.

6 Conclusions

It has been seen that changes in the climate and the weather will affect the solid waste infrastructure and that the largest effects will be due to flooding both in terms of disruption to the transport networks affecting collection and movement of wastes and to the waste infrastructure, although more research is needed to quantify the latter. Flooding will lead to a localised increases in waste arisings and it is likely that a typical household or business will create the equivalent of at least three months' worth of normal waste arisings following flooding. The actual levels of flood waste may be much higher than this and further research is needed to establish this. These flood events are predicted to become more frequent and bigger.

There is also a need to determine the costs of increasing the resilience of the waste sector.

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