

## **Waste Management and Research**

### **Evaluating the progress of UK's Material Recycling Facilities (MRFs) – A Mini Review**

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#### **Abstract**

Over the last 15 years, the UK has made great strides in reducing the amount of waste being sent to landfill while also increasing the amount of waste being recycled. The key drivers for this change are the EU Landfill Directive (1999/31/EC) European Parliament (1999) and the UK Landfill Tax (The Landfill Tax Regulations, 1996) However, also playing its part are the growing numbers of Material Recycling Facilities (MRFs) which process recyclables.

This mini-review evaluates the current state of MRFs in the UK, through extensive secondary research, and detailed primary data analysis focussing on MRFs located in the South-East England, UK. This study also explores technologies which aim to generate energy from waste, including Waste-to-Energy (WtE) and Refuse-Derived Fuel (RDF) facilities. These facilities can have a huge appetite for waste, which can be detrimental to recycling efforts as some of the waste being sent here should be recycled.

It was found that the waste sent to a typical UK MRF would recycled around 92% of materials while 6% was sent to energy recovery and the remaining 2% ended up in the landfill. Therefore, the total estimated rejected or non-compliance materials from MRFs are around 8%.

A key recommendation from this study is to adopt a strategy to combine MRFs with a form of energy generation, such as WtE or RDF. This integrated approach would ensure any residual waste arising from the recycling process can be used as a sustainable fuel, while also increasing the recycling rates.

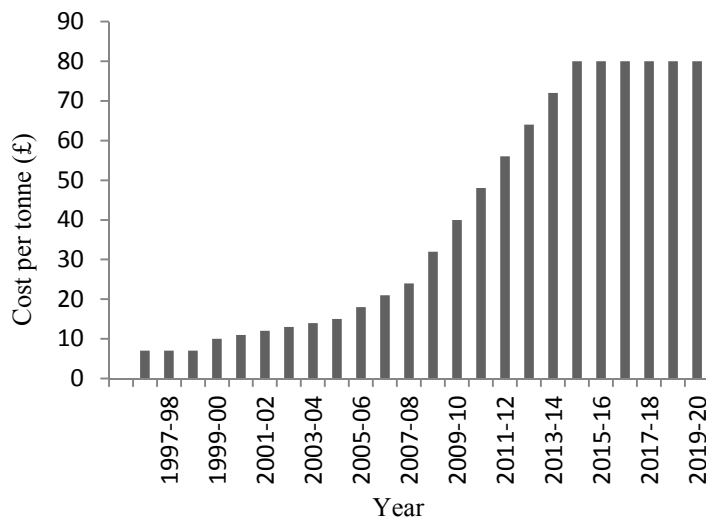
Keywords: Material Recycling Facilities, Energy from waste, Recycling, Material characterisation, Sustainable fuel.

## **Introduction**

It is widely agreed that the United Kingdom, UK's past reliance on landfill is now no longer an appropriate or a sustainable option. This history of landfilling has meant that when it comes to resource recovery and recycling, the UK has fallen well behind of its economic and geographical neighbours. For example, Mühle et al. (2009) compared Municipal Solid Waste (MSW) management of the UK and Germany. Data from European Commission, Eurostats (2012) showed that both countries have similar per capita waste generation (approximately 500-520 kg per annum) and both produce waste marginally above the EU average (503 kg per annum). However, Germany has one of the highest recycling rates (62%) in Europe (European Environment Agency, 2013) and also extracts significant energy from residual waste via combustion in Energy from Waste (EfW) facilities. In contrast, the UK remains highly dependent on landfill, where it sent 33.8% of waste to landfill in year 2012/13 (DEFRA, 2013).

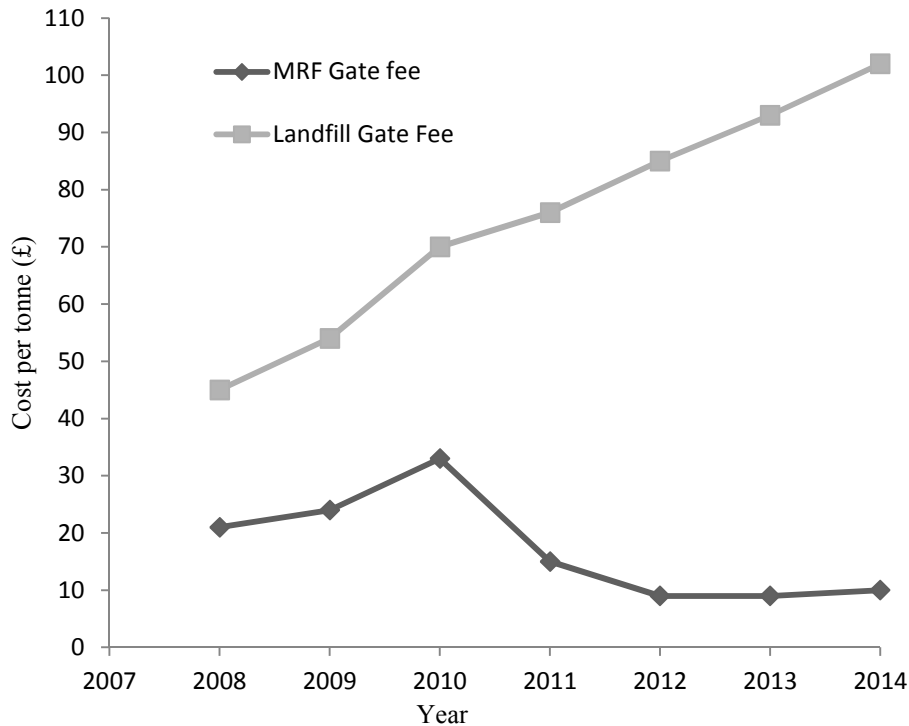
Germany is close to achieving a sustainable and environmentally friendly MSW management system, resulting from major developments over the last 20 years. Legislation introduced since the 1990s has had beneficial effects for Germany. These include a landfill ban on recoverable waste and compulsory source separation, allowing the creation of large amounts of homogeneous recyclables. Tightened waste acceptance criteria for landfills (Dehoust et al, 2005), along with promotion of more environmentally friendly EfW, recycling and composting has forced local authorities to change their ways (Mühle et al., 2009) with the ultimate aim of completely recovering MSW by 2020 (Verbüchelen et al, 2005).

The UK Government has proposed a series of initiatives, regulations and legislations to help change the UK's waste industry such as the Waste Strategy for England 2007 (DEFRA, 2007) and the landfill allowance trading scheme (LATS, 2004). The landfill tax regulation was originally introduced in 1996 with a standard rate for 'active waste' such as plastics of £7 per tonne and a lower rate for 'inactive waste' such as building rubble of £2 per tonne (The Landfill Tax Regulations, 1996). Since 1999, the rate of tax for active waste was increased by £1 per year per tonne, then by £3 per year starting in 2005, and then by £8 per year starting in 2007. Figure 1 displays how the rate of tax for active waste has increased with time (Seely, 2009). It is important to note that since the implementation of a landfill tax in August 1996 the tax rate has reached to a massive £80 per tonne in April 2014 (Her Majesty's Revenue and Customs, UK 2014). This rise in landfill tax aims to change the solid waste management culture of private industry and public authorities. Introducing a heavy levy on waste sent to landfill will help reduce the amount of waste being sent there, forcing businesses and government to explore more sustainable waste management routes. This tax increase is now resulting in landfilling becoming an increasingly unfeasible option. Furthermore, the UK government has decided to maintain the 2014 rate of £80 per tonne as a base rate until year 2020 (see Figure 1) which actually means that this rate is likely to go even higher in future ((Letsrecycle, 2013a). However, merely punishing organisations that dump their waste in landfill is not a sustainable option. Therefore, the UK has to improve measures that promote recycling and reuse of waste, making resource recovery a financially viable option.



**Figure 1.** Rate of Landfill tax in the UK

The gate fee is another financial driver which favours MRFs development in the UK. It is the waste handling fee charged by the waste management companies (Aylott, 2012). The median gate fees for waste recycling options are substantially lower than those for other waste disposal routes (WRAP, 2012). It can be seen in Figure 2 that the cost of disposal to landfill has increased due to the escalating landfill tax while the gate fees at MRFs have fallen substantially during the same time period. Many local authorities surveyed in this research are not paying gate fees or are receiving net revenue for their recovered materials. It is worth mentioning that all new local authorities MRF contracts in England from year 2013/2014 will pay £0 per tonne gate fee (WRAP, 2014) compared with -£7 per tonne for those signed in 2012, which means that they are actually receiving a median income of £7 per tonne (WRAP, 2013a). Whereas, gate fees in Scotland, Wales and Northern Ireland are notably higher than those in England (WRAP, 2011).



**Figure 2.** A comparison of gate fee charges between landfill and MRF

With regard to gate fees at WtE plants there is evidence that as the level of gate fees goes down, the amount of energy generated goes up. This inversely proportional relationship has been experienced in Denmark, a country with the lowest gate fees in Europe (Anderson, 2006).

Material Recycling Facilities (MRFs) are utilised to process the recycling and recovery of waste (WRAP, 2013b), and they play a vital role in the future of the UK's recycling industry. Source-segregated and commingled recyclables are delivered to MRFs, where they are screened and separated into their various fractions such as paper, plastic and aluminium.

These fractions are then finally baled and sent externally so that they can be made into new products.

The technology employed in these MRFs has grown exponentially in the UK over the last 15 years, and in order for the UK to meet its demanding recycling targets the use of this technology must continue to grow.

### **Review of the current situation**

This study looks at the role of MRF's in the UK's Waste Management Industry and will try to establish MRF's relationship with Waste-to-Energy (WtE) Plants in the UK. Unlike other waste-based energy sources, WtE is compatible with recycling. Evidence from progressive European countries suggests that a high level of WtE and recycling can coexist (DEFRA, 2006). Whereas, research conducted in the United States (US) from 2002 shows that communities who employ WtE recycle 5% above the US average (Chester et al., 2007). Further investigations conducted by Berenyi (2009) supported this point, concluding that waste-to-energy does not have adverse impacts on recycling rates.

A study conducted by Kang and Schoenung (2006) on electronic waste suggested that by employing MRFs materials such as metals, plastics and glass from waste electronic products can be recycled to generate decent profits. Materials such as paper and plastics enjoy established recycling markets however paper tends to swiftly degrade in quality through the recycling process, while the wide variety of plastic types means some are more cost effectively recycled than others. Besides plastics used for food and medical packaging are unsuitable for recycling (Miranda and Hale, 1997) and the high proportion of these contaminated plastics found in MSW can generate high amounts of energy from WtE (Porteous, 2005).

It is generally agreed that in terms of climate change waste prevention is the best strategy, followed by reuse and recycling, landfill and incineration (Friends of the Earth, 2006). Recent advances in waste treatment have shown that in fact Anaerobic Digestion (AD) provides an opportunity to generate both a soil improver and energy in the process (Hogg, 2006) hence, it is possibly the most climate friendly option in terms of total CO<sub>2</sub> and total SO<sub>2</sub> saved (Evangelisti et al., 2014). However, AD is predominantly designed for the treatment of source-separated wet organic waste, kitchen waste (Zhang et al., 2007) and animal manure (Wei et al., 2014). Whereas, recycling is more suited to manage dry recyclates, and recovering a considerable amount of materials (Menikpura et al., 2014).

A comparative study conducted by Chilton et al. (2010) on recycling and energy recovery of waste polyethylene terephthalate (PET) bottles showed that recycling of PET bottles resulted in an overall reduction in the emission of CO<sub>2</sub>, particulate matter and other harmful gases. Nevertheless, there are also some issues related to recycling such as the cost of the process is relatively high due to the technology and sorting required. Furthermore, its inability to recover energy is a concern when renewable energy production is a high priority for the UK. Waste-to-energy can limit the amount of waste sent to landfill and help the UK meet its renewable energy targets (Jamash & Nepal, 2010).

### *Refuse Derived Fuel (RDF)*

Rather than simply burning waste as it comes in, it is possible to convert waste into a storable fuel. RDF can be in many different forms, including powders, bales and pellets (Buekens, 2013). Technology employed in MRFs is used in the screening process for RDF production. Near Infrared (NIR) spectroscopy is often used in the detection and removal of

polyvinylchloride (PVC), as well as selectively sorting and processing suitable fuel components such as wood, paper, textiles and certain plastics. Arafat et al. (2013) recommended that in terms of energy recovery recycled paper, wood and plastic are ideal. Solid recovered fuel (SRF) is also produced using MRF technology such as air classification, eddy current and magnetic separation. These negative sorting steps remove unwanted heavy and inert materials (Christensen, 2010). Similarly, Garg et al. (2009) suggested that SRF can be utilised as an alternative to fossil fuel, particularly for the energy intensive processes.

### *Clean and Dirty MRFs*

Clean MRFs process waste after source segregation of dry mixed recyclates has occurred, usually at the kerbside collection stage. Dirty MRFs recover waste directly from MSW (Owen et al., 2007), meaning no prior sorting by residents, businesses and councils is needed. Hence, there are advantages and disadvantages for both operations (Griffiths et al., 2010). Apart from economic and environmental benefits MRFs can have positive effects on both social and human health issues (Dubanowitz, 2002).

Due to prior sorting at clean MRFs recovery is high, at over 90 per cent. Other advantages include higher processing efficiency and better working conditions. Clean MRFs are also well proven throughout the world. Downsides to this operation include a high reliance on the participation and quality of kerbside collection schemes, as well as the need for separate collection rounds for recycled material. This extra collection can have negative environmental impacts on air quality and traffic movement (Griffiths et al., 2010).

Dirty MRFs typically produce 15-20 per cent of its feedstock as dry recycled material. More advanced facilities are able to recover biodegradable material for anaerobic digestion and composting, while high calorific material can be processed for RDF production. No added collection infrastructure is needed, as dirty MRFs utilise the current systems, meaning no



added environmental impacts. Participation is in theory 100 per cent, as residents and businesses do not need to change their behaviour. Disadvantages include contamination of recyclables with food waste, which in turn can have negative impacts on the performance of the MRF and the quality of the recovered recycled material. It can also be said that use of this system can make the general public complacent, as there would be less need for them to change their waste management habits, with the waste hierarchy encouraging everyone to reduce, reuse and recycle their waste.

### *MRF Capacity*

Waste Resource Action Program (WRAP) UK commissioned a report- 'MRFs Comparison of efficiency and quality' (WRAP, 2006a), which highlighted that a number of MRF facilities were in the planning process (or recently received planning consent), with some large capacity facilities of 100,000 tonnes per annum or above. This apparent movement towards larger MRFs follows the trend in other countries where the cost efficiency of sorting larger volumes of material at a single MRF, operating two or three shifts a day, is recognised (WRAP, 2006a). This WRAP's report compared MRFs in England with those run in Europe and North America. Most MRFs in Europe and North America are large scale (above 50,000 tpa). This appears to be a likely trend within England, as well as the rest of the UK, in coming years.

European and North American MRFs seem to operate too much tighter standards, such as lower levels of contamination (WRAP, 2006a). The Quality Control (QC) measures are much stricter, with specific inspection procedures, while in England QC is mainly carried out through visual inspection (WRAP, 2006a).

Six out of seven MRFs WRAP investigated in England do not accept glass containers in the incoming stream. However, the newer MRFs appear to have incorporated single-stream co-mingled material including glass (WRAP, 2006a).

### *MRF Technology*

The configuration of a MRF processing line is dependent upon how the materials are received. The two main varieties of incoming waste are either source segregated and co-mingled. Most MRFs in the UK operate single stream systems, either including glass or processing glass separately (WRAP, 2011). A variety of waste sorting machines arrangements can be adapted depending upon the MRFs designer for example a typical modern MRF can start with Trommel or Star Screens for removal of large objects such as oversized carton and cardboard (OCC) screens, magnetic separator for iron-based metals, Near infrared spectroscopy and Optical sorters for separation of dense plastics while aluminium can be separated by employing eddy current technology.

### *MRF Code of Practice*

A code of practice for MRFs was launched for consultation in February 2013 by Department of Food and Rural Affairs (DEFRA), UK, which in February 2014 became part of amendments to the Environmental Permitting (England and Wales) Amendment Regulations 2013 (Defra, 2014). These have now been laid before the UK's Parliament and are due to come into effect in October 2014. This code of practice requires all MRFs processing more than 1,000 tonnes per annum dry recyclables to routinely measure the quality of their input, output and residual streams. Table 1 shows proposed a sampling and testing regime for MRFs.

**Table 1.** Summary of proposed levels of sampling under the MRF code of practice (Source: Letsrecycle 2013b)

	<b>Sample Weight (kg)</b>	<b>Time based frequency*</b>	<b>Time based frequency*</b>
<b>Mixed Input</b>	25	2 per week or	1 per 200T
<b>Residual Stream</b>	20	1 per week or	1 per 100T
<b>Paper (per output stream)</b>	20	1 per week or	1 per 100T
<b>Glass (per output stream)</b>	10	1 per week or	1 per 50T
<b>Metals (per output stream)</b>	20	1 per week or	1 per 20T
<b>Plastics (per output stream)</b>	20	1 per week or	1 per 20T

\*whichever is most frequent

The overall aim of the new code of practice is to drive up quality and standards of the recyclable content, in so making it more economically beneficial. These regulations also intend to demonstrate that collection and MRF processing of commingled dry recyclables deliver to the requirements set out by the EU revised Waste Framework Directive, which were formally enshrined in the UK law in February 2011 (Letsrecycle, 2013c) and produce high quality recycling. DEFRA also intend for this information to be published to allow greater transparency with existing and prospective clients, as well as the general public (Letsrecycle, 2013b).

It is believed that new MRF Code of Practice (Defra, 2014) should improve the overall standards of MRFs through regular sampling and testing of material inputs. However it perceived that this increased accountability of MRFs would drive up their prices, meaning future government-MRF contracts could be more expensive.

Optical sorting technology is something which has greatly improved over the last 10 years, and it is predicted improve further in near future. Germany is already utilising advance optical measuring technology to record paper quality. These optical sensors identify the percentage of contras/non-compliant material going through the MRF, and also identify the quality of a batch of paper being sent to a paper mill. This means that quality analysis, which is generally carried out manually could be fully automated in the future. This can lead to a more accurate and comprehensive picture of the material processed by a MRF, as all the material will be recorded rather than just relying on a grab sample. Furthermore the MRF code of practice will require all large MRFs to record the material they process, meaning acquisition of technology which helps to measure the material composition should be a top priority. Moreover, the residuals' produced through the MRF process are usually of very high calorific value, and would be perfectly utilised for RDF production. This point further links the potential future development of plants that process waste for both recycling and energy production.

## **Research Methods**

The work presented in this paper highlight the current state of MRFs in the UK, through an extensive secondary research, as well as primary data analysis. The primary sources of information obtained in this investigation included various site visits and interviews with the MRF operators. While, the secondary research stems from published statistics and data obtained from the UK Government's past investigations and reports.

This review also explores technologies which aim to generate energy from waste, including Waste-to-Energy (WtE) and Refuse-Derived Fuel (RDF) facilities. These facilities can have a

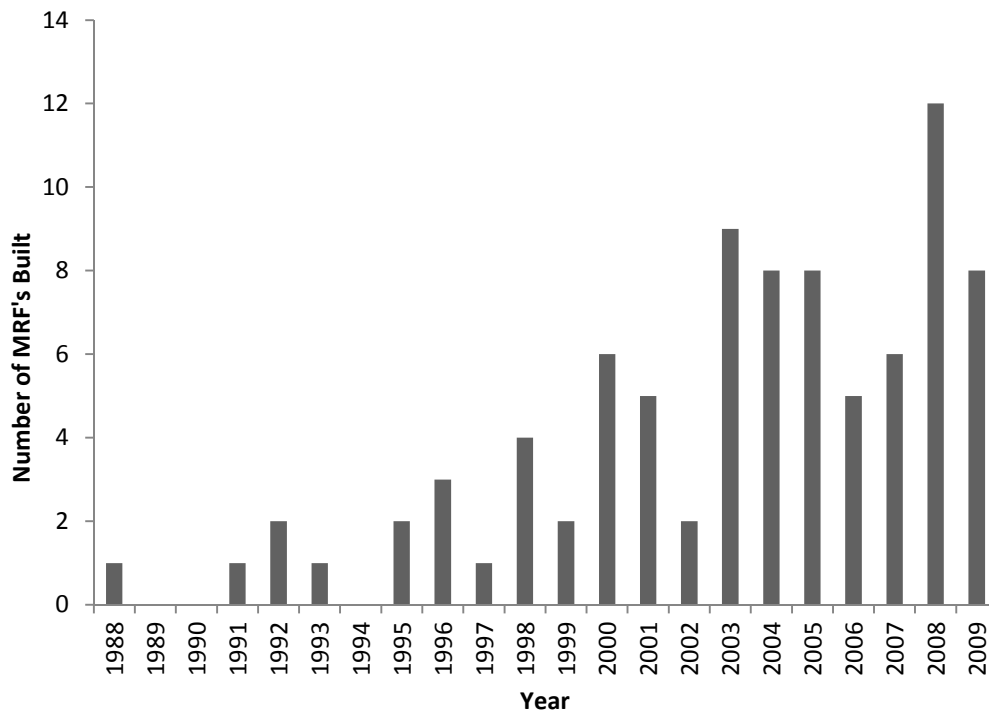
huge appetite for waste, which can be detrimental to recycling efforts as some of the waste being sent here should be recycled.

### **Discussion and Analysis of the data**

The UK has made good progress in improving recycling rates whilst also lowering the amount of waste sent to landfill. The rise in recycled waste could be linked with the introduction of major legislation, especially the EU Landfill Directive, European Parliament (1999). It is due to these legislations that we are now observing an increased proportion of waste being recycled and composted, whilst also decreasing the proportion of waste being sent to landfill. For example, the household recycling rate and landfilling in England for year 2000/01 were 11.2% and 76% respectively but in year 2012/13 the recycling rate has jumped to 43.2%, while the amount of landfilling is reduced to 33.8% (WasteDataFlow, 2013). This represents an encouraging trend, however further progress must be made to ensure even less waste is being sent to landfill in the future.

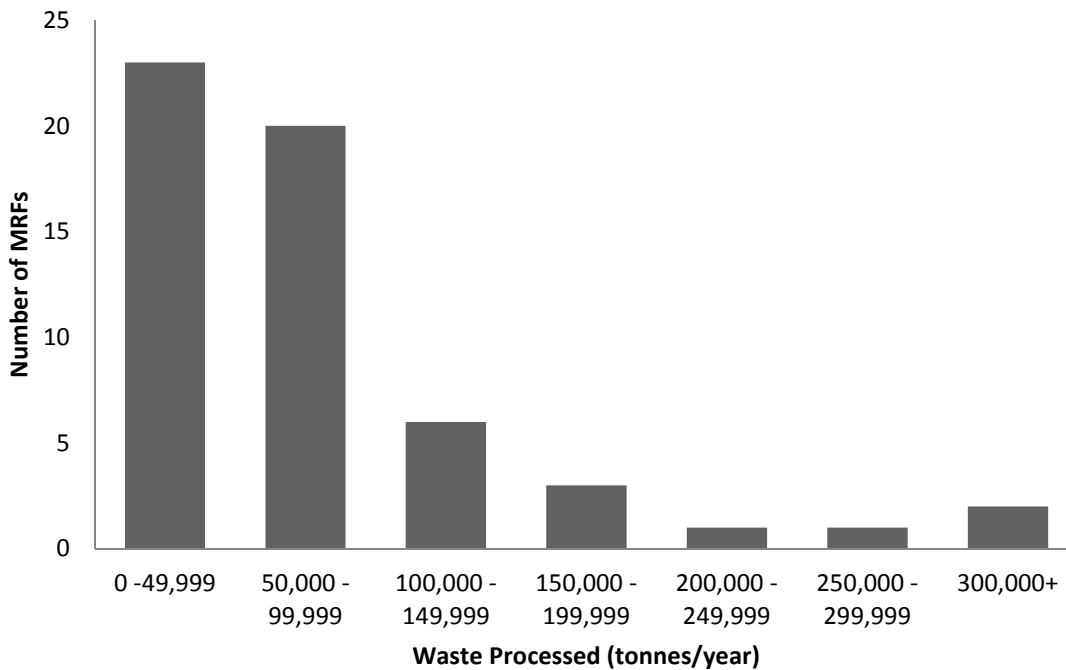
#### *MRF Development in the UK*

Figure 3 shows the number of MRFs opened in the UK over time. It is evident that the vast majority of these facilities have been constructed over the last ten years. It can also be seen that 65% of MRFs were built in a six year period between 2003 and 2009. This shows that the UK has been playing catch up when it comes to the development of MRFs. However, the trend for recent high levels of investment in MRFs is encouraging. It is also important to note that the rise in the UK's recycling rates could be due to the increased number of MRFs opened in the last decade.



**Figure 3.** MRFs built over time

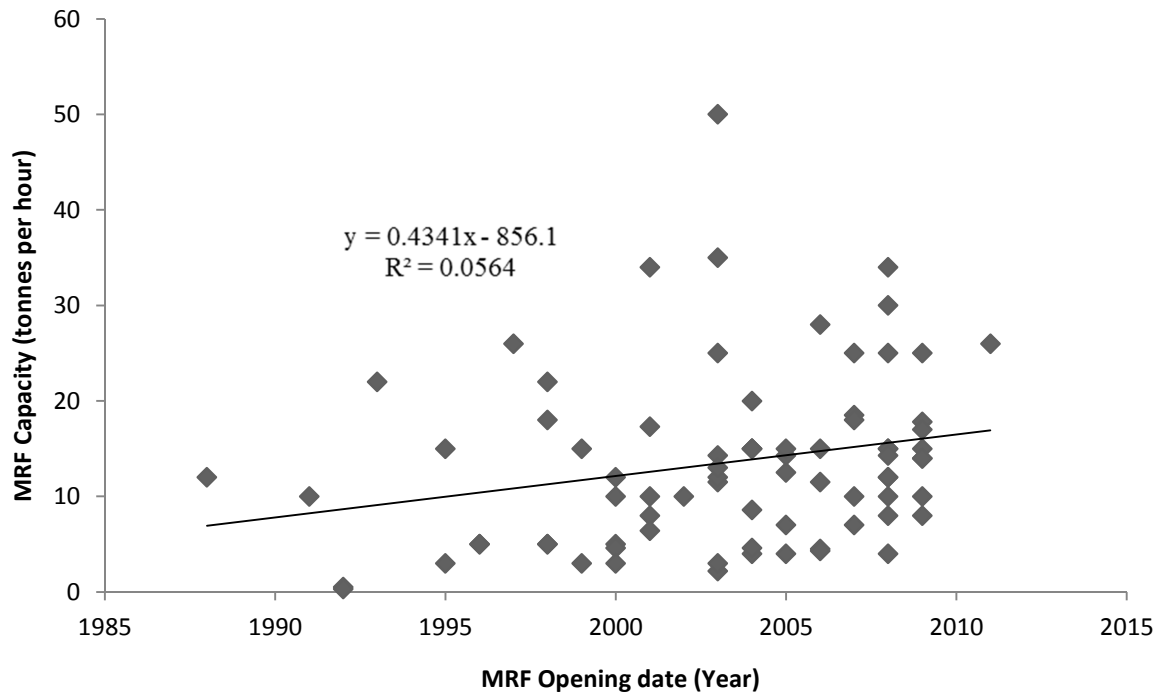
Material Recycling Facilities can come in a broad range of sizes, and as such operate to a wide range of capacities. Figure 4 shows the processing capacity of the UK’s MRF. Out of the 97 UK MRFs identified, waste processing data was obtained from 57 of them. This represents nearly 60% of all UK MRFs, allowing these results to be a fairly accurate representation. The result shows that the majority of UK MRFs investigated have processing capacities above 50,000 tonnes per annum. This follows the trend predicted by WRAP (WRAP, 2006a), suggesting the UK has followed the approach adopted by North America and some European countries to focus on bigger facilities.



**Figure 4.** MRFs operating at a range of waste processing capacities

Figure 5 highlights the relationship between the maximum capacities of MRF's with respect to their initial operation. It can be seen that there is a weak positive correlation between MRF opening date and higher operating capacity. This upward trend of operating capacity also supports the recommendations made by WRAP. The line of best fit shows a doubling of average operating capacities between the mid 90s to the present day. This underlines the point that developing MRFs with larger operating capacities is the focus of future growth.

The trend of decreasing levels of waste generated, due to a mixture of successful government initiatives and recessionary impacts means the focus of future growth of MRFs should be the processing of a greater variety of waste. This should include unrecyclable residuals which can be recovered. Operators of large MRFs should be encouraged to investigate whether some form of energy recovery could be employed on their site.



**Figure 5.** MRF opening date against MRF capacity

Once material for recycling is collected, it is sent to transfer stations, and then to the MRFs. Although the vast majority of material delivered to MRFs is recyclable, there is a small proportion which is unsuitable. This material is consequently rejected and disposed of externally, possibly to the landfill.

The MRFs chosen for this paper represented a wide range of operating companies, sizes and locations around the UK, thus, giving a good indication of how MRFs operate in the UK as a whole. The MRFs selected for this study were located in Portsmouth, Southampton, Tower Hamlets, Westminster, Rhondda Cynon Taff County Borough Council, Leicester, Peterborough and Plymouth, UK.

It was found that on average 92% of the recycled waste arrived at these MRFs was suitable for recycling, 6% was deemed suitable for energy recovery while the remaining 2% was sent to landfill. These figures suggest that the selected MRFs are suitably built to recycle waste. It



is also encouraging to see that the majority of local authorities send their rejected waste to energy recovery rather than landfill. A possible reason for this could be the high cost of sending waste to landfill caused by the landfill tax.

The Portsmouth MRF operators estimated that typically 10% of the total waste sorted is judged to be non-compliant or residual. These materials do not meet the specifications of the MRF for recycling, and are sent to landfill or energy recovery. This is a considerable percentage of the total waste, and if this proportion were to be scaled up it would mean that for a MRF the size of Portsmouth's (78,000 tpa), the total rejected material would be nearly 8,000 tonnes per annum.

The percentage of rejected material established for Portsmouth MRF correlates strongly with the findings for seven other UK MRFs, which showed an average of 8% rejected material. Therefore, it can be assumed that MRF processing currently works to a rejected rate of between 8-10%.

There are a number of possible reasons why this percentage of non-compliant material is finding its way to the MRF, these include:

- Lack of awareness/education of local residents about what they are allowed to recycle.
- Incoming recyclables are heavily contaminated, and are inappropriate for recycling.
- MRFs do not have the required plant and technology to process this rejected material.
- There may not be a sufficient end-market demand and value for these materials to justify investing in machinery to process them.

Discussions with staff at the Portsmouth MRF also highlighted the challenges in predicting the waste flow coming into the MRF from day to day. Prediction is necessary as, depending

on the incoming waste, the MRF system will need to be altered appropriately to accommodate for the incoming recyclables. For example, there may be periods of time in the summer months where there is a higher frequency of aluminium drink cans and cardboard boxes in the waste stream, and as such the MRF system will be geared to cope with this change in waste flow. It was also established that the greater influx of plastics such as yogurt pots and similar food-based recyclable, which are currently very difficult to process, and are therefore rejected. However, there is evidence that this can certainly be improved by educating the local community (Perrin and John, 2001). Furthermore, Greater investment in technology, especially NIR spectroscopy in this case, would help reduce the plastic being rejected at Portsmouth plant and can increase the total proportion of recycled material.

### *Energy Recovery*

As discussed before, although the UK has enjoyed very encouraging increases in waste recycling, there is still a high proportion of waste sent to landfill (Wastedataflow, 2013). It is thought that this high level of landfilling in the UK is partly due to very little waste currently being sent for energy recovery. Incineration, WtE and RDF technology can be employed to process waste into energy. However, there are arguments about the environmental and economical validity of building these plants, especially in low populated areas. According to Leonard (2013) the UK government is planning to build more large scale facilities. These plants have an enormous hunger for waste, which will usually outlast the supply from the local area. This means waste will be needed from elsewhere to keep the facility operating. Examples from other countries, including Denmark, claim that this high demand for burning waste can undermine efforts to recycle. Furthermore, much of the waste being sent to incinerators is completely recyclable. Large-scale incinerators can also damage efforts to

reduce the total waste generated, as they are encouraging waste to be produced in order to keep the facility operating.

An integrated approach linking MRFs and energy recovery should be taken to ensure waste recovery is utilised. Building plants with the ability to recycle waste, whilst also recovering energy from the remaining unrecyclable residual waste, would ensure that all waste would be dealt with in the appropriate manner. Work conducted by Chen and Chen (2013) on Taiwan's MSW waste management policy also emphasise on integrating recycling with energy recovery. They also highlighted the potential benefits by combining the two techniques such as conservation of natural resources, enhancement in the design life of waste disposal sites as well as fall in secondary pollution. Similarly, Consonni and Vigano (2011) found that residual materials after recycling had higher caloric values compared to unsorted residual waste. Therefore, it appears that there is a positive relation between the materials rejected from MRFs to the potential energy recovery. Furthermore, if a single company were to operate facility then there will be no financial incentive to burn waste which should have been recycled. The MRF technology would not only sort different types of recyclables, but it would also screen unrecyclable material, therefore, utilising technologies that can deliver alongside already operational MRFs.

## **Conclusions**

It is clear that recycling and MRF development has radically increased over the last 15 years, and current evidence suggests that this trend is set to continue into the future. The key drivers for the changes are both EU and the UK Government's Legislations that forced waste to be diverted from landfills.

It is evident that the UK cannot rely entirely on recycling for the future of solid waste management, recycling is just not viable for some waste, such as organic waste and certain types of plastics. Composting and anaerobic digestion should be utilised to deal with all organic and biodegradable waste, while RDF and Waste-to-Energy processing is vital in keeping waste management as sustainable as possible.

Material Recycling Facilities should be further developed to ensure all the materials that can be recycled are recycled. An integrated approach to waste management could ensure that recycled as much waste as possible. Refuse derived fuel and WtE processing should only be made once the waste has been screened using MRF technology. Therefore, establishing facilities that accommodate MRF processing and RDF/incinerators should be adopted. The MRFs should be the first port of call for waste to ensure no recyclable material is wasted, while the remaining unrecyclable material should then be transferred to secondary RDF and incinerator processing to produce energy from this residual waste.

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### **References**

Anderson PH (2006) The Danish model. Presentation by Ramboll; October 2006.

Arafat HA, Jijakli K and Ahsan A (2013) Environmental performance and energy recovery potential of five processes for municipal solid waste treatment, *Journal of Cleaner Production*, 1, 8.

Aylott, M (2012) Analysis: Gate fees fall but energy from waste industry remains buoyant. NFFCC the bio economic consultants.

Berenyi E (2009) *Recycling and Waste-to-Energy: Are They Compatible?*. Westport, CT: Governmental Advisory Associates, Inc.

Buekens A (2013) Incineration Technologies: Refuse-Derived Fuel. Springer Briefs in *Applied Sciences and Technology* 2013, pp 71-76.

Chen C-C and Chen Y-T (2013) Energy recovery or material recovery for MSW treatments? *Resources, Conservation and Recycling*, 74, 37– 44.

Chilton, T Burnley S Nesaratnam S (2010) A life cycle assessment of the closed-loop recycling and thermal recovery of post-consumer PET, *Resources, Conservation and Recycling*, 54 (12), 121241–1249.

Chester M, Plevin R Rajagopal D and Kammen D (2007) *Biopower and waste conversion technologies for Santa Barbara County*. Report for the Community Environmental Council. Berkeley Affiliates. University of California. Final Report.

Christensen TH (eds.) (2010) *Solid Waste Technology & Management*. Chichester: John Wiley & Sons, Lt Chichester , ISBN: 978-1-405-17517-3.

Consonni S and Vigano F (2011) Material and energy recovery in integrated waste management systems: The potential for energy recovery, *Waste Management* 31, 2074–2084.

DEFRA (Department of Environment Food and Rural Affairs) (ed.) (2006) *Review of England's waste strategy- a consultation document, summary of responses to the consultation*. London.

DEFRA (ed.) (2007) Waste Strategy for England 2007. Available at <http://archive.defra.gov.uk/environment/waste/strategy/strategy07/documents/waste07-strategy.pdf> (accessed 1 September 2014).

DEFRA (ed.) (2011) *Waste Data Overview- June 2011*. Available at <http://www.defra.gov.uk/statistics/files/20110617-waste-data-overview.pdf> (accessed 21 January 2013).

DEFRA WasteDataFlow (ed.) (2013) *WasteDataFlow Data Manager*. Available at <http://www.wastedataflow.org/news/welcome.aspx> (accessed 9 January 2013).

DEFRA (ed.) (2014) *Draft Materials Recovery Facility (MRF) Regulations for insertion into Environmental Permitting (England and Wales) (Amendment) Regulations*. Available at <http://www.gov.uk/government/consultations/draft-materials-recovery-facility-mrf-regulations-for-insertion-into-environmental-permitting-england-and-wales-amendment-regulations-2013> (accessed 4 March 2013).

Dehoust G, Wiegmann K Fritsche U Jenseit W Herold A Comes M and Gebhardt P (2005) Status report on the contribution of waste management and climate protection possible potentials. BMU. Research Report 2005, 205 (33): 314.

Dubanowitz AJ (2000) Design of a Materials Recovery Facility (MRF) For Processing the Recyclable Materials of New York City's Municipal Solid Waste Department of Earth and Environmental Engineering, Fu Foundation School of Engineering and Applied Science, Masters Dissertation, Columbia University.

Eurostat (ed.) (2012) *Eurostat Interactive graph*. Available at [http://www.epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/sectors/municipal\\_waste](http://www.epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/sectors/municipal_waste) (accessed 13 March 2013).

European Parliament (1999) Directive 1999/31/EC on the landfill of waste. Official Journal L 182, 16/07/1999 P 0001 - 0019. Available at <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31999L0031>(accessed 1 September 2014). European Environment Agency (2013) Managing municipal solid waste - a review of achievements in 32 European countries. EEA Report No 2/2013 (accessed 1 September 2014).

Evangelisti S, Lettieri P Borello D and Clift R (2014) Life cycle assessment of energy from waste via anaerobic digestion: A UK case study, *Waste Management*, 34 (1), 226–237

Friends of the Earth (2006) Dirty Truths Incineration and climate change. Available at [http://www.foe.co.uk/sites/default/files/downloads/dirty\\_truths.pdf](http://www.foe.co.uk/sites/default/files/downloads/dirty_truths.pdf) (accessed 4 September 2014).

Garg A, Smith R Hill D Longhurst PJ Pollard SJT and Simms NJ (2009) An integrated appraisal of energy recovery options in the United Kingdom using solid recovered fuel derived from municipal solid waste, *Waste Management* , 29(8), 2289–2297

Griffiths A J, Williams K P and Owen N (2010) *Engineering value recovery from municipal solid waste*. Proceedings of the Institution of Mechanical Engineers, Part C: *Journal of Mechanical Engineering Science*, 224, 559-570.

Her Majesty Revenue and Customs (2014) Landfill tax briefs – March 2014. Available at [http://www.entrust.org.uk/assets/uploads/documents/Budget\\_2014\\_Landfill\\_Tax\\_Briefing.pdf](http://www.entrust.org.uk/assets/uploads/documents/Budget_2014_Landfill_Tax_Briefing.pdf) (accessed on 1 September 2014).

Hogg, D (2006) A Changing Climate for Energy from Waste? Final report to Friends of the Earth, Eunomia research and consulting.

Jamasb T and Nepal R (2010) Issues and options in waste management: A social cost–benefit analysis of waste-to-energy in the UK. *Resources, Conservation and Recycling*, 54, 1341–1352.

Kang, HY and Schoenung JM (2006) Economic Analysis of Electronic Waste Recycling: Modeling the Cost and Revenue of a Materials Recovery Facility in California, *Environmental Science and Technology* 40, 1672-1680.

Leonard H (2013) *Costing the Earth* [Radio broadcast, 19<sup>th</sup> February]. London: BBC Radio 4.

Letsrecycle (2013a) *Landfill Tax: in partnership with DSS Smith recycling*. Available at <http://www.letsrecycle.com/business/landfill-tax> (accessed 14 April 2013).

Letsrecycle (2013b) *Long-awaited MRF Code of Practice unveiled*. Available at <http://www.letsrecycle.com/news/latest-news/waste-management/long-awaited-mrf-code-of-practice-unveiled> (accessed 20 February 2013).

Letsrecycle (2013c) *Waste Framework Directive: in partnership with DS Smith recycling*. Available at <http://www.letsrecycle.com/business/waste-framework-directive> (accessed 12 December 2012).

Menikpura SNM, Santo A and Hotta Y (2014). Assessing the climate co-benefits from Waste Electrical and Electronic Equipment (WEEE) recycling in Japan, *Journal of Cleaner Production*, 74 (1), 183–190.

Miranda ML and Hale B (1997) Waste not, want not: the private and social costs of waste-to-energy production. *Energy Policy*, 25(6), 587–600.

Mühle S, Balsam I and Cheeseman CR (2009) Comparison of carbon emissions associated with municipal solid waste management in Germany and the UK. *Resources, Conservation and Recycling*, 54, 793-801.

Owen N, Griffiths AJ and Williams KP (2007) *Dirty materials recycling facilities (MRF) and their role in assisting a UK local authority to divert waste away from landfill*. In Proceedings of the 22<sup>nd</sup> Solid Waste Technology and Management Conference, Philadelphia, USA, 417–424.

Perrin D and Barton J (2001). Issues associated with transforming household attitudes and opinions into materials recovery: a review of two kerbside recycling schemes, *Resources, Conservation and Recycling*, 33 (1), 61–74.

Porteous A (2005) Why energy from waste incineration is an essential component of environmentally responsible waste management. *Waste Management*, 25, 451–9.

Seely A. (2009a) *Landfill tax: introduction & early history*. Westminster: House of Commons. Available at <http://www.parliament.uk/business/publications/research/briefing-papers/SN00237/landfill-tax-introduction-early-history> (accessed 2 September 2014).

The Landfill Tax Regulation (1996) Landfill tax 1<sup>st</sup> August 1996, 1996 No. 1527. Available at <http://www.legislation.gov.uk/ukxi/1996/1527/contents/made> (accessed 2 September 2014).

The Landfill Allowances and Trading Scheme (England) Regulations, LATS (2004). Environment Protection England, 2004 No. 3212. Available at [http://www.legislation.gov.uk/ukxi/2004/3212/pdfs/ukxi\\_20043212\\_en.pdf](http://www.legislation.gov.uk/ukxi/2004/3212/pdfs/ukxi_20043212_en.pdf) (accessed 1 September 2014).

Verbüchelen M, Hansen W Neubauer A Kraemer RA and Leipprand A (2005) Strategy for the future of waste management (target 2020). BMU 201 R & D projects 2005, 32:324.

Wei S, Zhang H Cai X Xu Jin Fang Jiangping and Liu Heman (2014). Psychrophilic anaerobic co-digestion of highland barley straw with two animal manures at high altitude for enhancing biogas production. *Energy Conversion and Management*, 88, 40–48.

WRAP (Waste and Resources Action Programme) (ed.) (2006a) *MRFs Comparison of efficiency and quality*. Available at [http://www.wrap.org.uk/sites/files/wrap/MRF\\_v6\\_19Dec06\\_LC.pdf](http://www.wrap.org.uk/sites/files/wrap/MRF_v6_19Dec06_LC.pdf) (accessed 27/10/12).

WRAP (ed.) (2006b) *Environmental benefits of recycling: An international review of life cycle comparisons for key materials in the UK recycling sector*. Available at <http://www.wrap.org.uk/content/environmental-benefits-recycling> (accessed 25 May 2013).

WRAP (ed.) (2011). Comparing the cost of alternative waste treatment options, Gate fee report July 2011. Available at <http://www.wrap.org.uk/sites/files/wrap/Gate%20Fees%20Report%202011.pdf> (assessed 1 September 2014).

WRAP (ed.) (2012). Comparing the cost of alternative waste treatment options, Gate fee report July 2012. Available at <http://www.wrap.org.uk/content/wrap-gate-fees-report-2012> (accessed 2 September 2014).

WRAP (ed.) (2013a). Comparing the cost of alternative waste treatment options, Gate fee report 2013. Available at [http://www.wrap.org.uk/sites/files/wrap/Gate\\_Fees\\_Report\\_2013\\_h%20%282%29.pdf](http://www.wrap.org.uk/sites/files/wrap/Gate_Fees_Report_2013_h%20%282%29.pdf) (accessed 3 September 2014).



WRAP (ed.) (2013b). *Sorting Materials - Materials Recovery Facilities (MRFs)*. Available at <http://www.wrap.org.uk/content/sorting-materials-materials-recovery-facilities-mrfs> (accessed 19 march 2013).

WRAP (ed.) (2014). Comparing the cost of alternative waste treatment options, Gate fee report 2014. Available at [http://www.wrap.org.uk/system/files/private/Gate\\_Fees\\_Report\\_2014.pdf](http://www.wrap.org.uk/system/files/private/Gate_Fees_Report_2014.pdf) (accessed on 3 September 2014).

Zhan R, El-Mashad HM Hartman K Wang F Liu G Choate C and Gamble P (2007) Characterization of food waste as feedstock for anaerobic digestion, *Bioresouce Technology* 98 (4), 929–935.