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The potential contribution of sustainable waste management to energy use and greenhouse gas emission reduction in the Netherlands

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ABSTRACT

Future limitations on the availability of selected resources stress the need for increased material efficiency. In addition, in a climate-constrained world the impact of resource use on greenhouse gas emissions should be minimized. Waste management is key to achieve sustainable resource management. Ways to use resources more efficiently include prevention of waste, reuse of products and materials, and recycling of materials, while incineration and anaerobic digestion may recover part of the embodied energy of materials. This study used iWaste, a simulation model, to investigate the extent to which savings in energy consumption and CO_2 emissions can be achieved in the Netherlands through recycling of waste streams versus waste incineration, and to assess the extent to which this potential is reflected in the LAP2 (currently initiated policy). Three waste streams (i.e. household waste, bulky household waste, and construction and demolition waste) and three scenarios compare current policy to scenarios that focus on high-quality recycling (*Recycling+*) or incineration with increased efficiency (*Incineration+*). The results show that aiming for more and high-quality recycling can result in emission reductions of 2.3 $MtCO_2$ annually in the Netherlands compared to the reference situation in 2008. The main contributors to this reduction potential are found in optimizing the recycling of plastics (PET, PE and PP), textiles, paper, and organic waste. A scenario assuming a higher energy conversion efficiency of the incinerator treating the residual waste stream, achieves an emission reduction equivalent to only one third (0.7 $MtCO_2$/year) of the reduction achieved in the *Recycling+* scenario. Furthermore, the results of the study show that currently initiated policy only partially realizes the full potential identified. A focus on highest quality use of recovered materials is essential to realize the full potential energy and CO_2 emission reduction identified for the Netherlands. Detailed economic and technical analyses of high quality recycling are recommended to further evaluate viable integrated waste management policies.

1. Introduction

To avoid major negative impacts of climate change, large reductions in greenhouse gas emissions are necessary. For industrialized countries, like the Netherlands, reductions of 60–80% in greenhouse gas (GHG) emissions are necessary by 2050 (IPCC, 2007). To achieve this, both energy and resources must be used far more efficiently. Secondly, future scarcity is an argument for increasing material efficiency (Allwood et al., 2011; IPCC, 2007). Within decades, shortages are expected for a number of strategic materials that are mainly used in electronic equipment (Cohen, 2007). Companies and countries are already making strategic decisions to ensure access to these essential materials. The European Commission has also recognized the importance of resource efficiency and made it one of the seven flagship initiatives that are part of the Europe 2020 strategy that aims to deliver sustainable, smart and inclusive growth. The focus on resource efficiency should help to achieve the European Union's targets on reducing GHG emissions, improving the security of supply of raw materials, and make the European economy more resilient to price increases of energy and commodities (European Commission, 2011).

Waste management is a key element in achieving sustainable resource management. Ways how waste management can contribute to efficient resource use include waste prevention and reuse and recycling of products and materials, while incineration and anaerobic digestion may recover part of the materials embodied energy of materials. The Netherlands has a long history in (research on) waste-to-energy and saving resources, and has been successful in the past to recover materials from waste. Waste and resource

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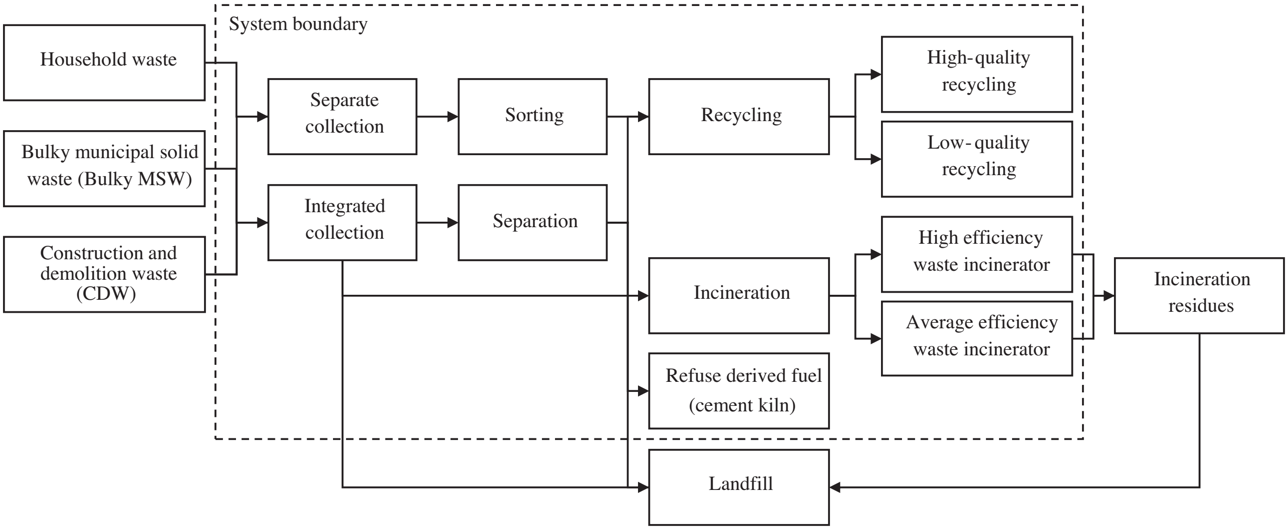

Fig. 1. Schematic representation of the system boundaries in this study. *Note*: between most of the processing steps a transport step is included, which is not depicted.

management was also central to the development of the second National Waste Management Plan (Landelijk Afvalbeheerplan, LAP2) in the Netherlands (VROM, 2010), which is implemented for the period 2009–2021. The LAP2 aims to

- Limit the total waste volume to 68 Mt in 2015 and 73 Mt in 2021 (60 Mt in 2006);
- Increase waste recovery to 85% in 2015;
- Increase municipal waste recovery from 51% in 2006 to 60% in 2015;
- Maintain recovery of construction and demolition waste at the 2006 level of 95%.

The LAP2 should also contribute to the reduction of GHG emissions, as set out in national policy, and will try to achieve this by focusing on recycling, anaerobic digestion and incineration.

This study investigates to what extent a further reduction of energy consumption and CO_2 emissions can be achieved through recycling of materials in selected waste streams, versus waste incineration with energy recovery. For this purpose a simulation model, called *i*Waste, is developed which is used for an exploratory (scenario) analysis of treatment options for selected waste streams in the Netherlands. The *i*Waste model simulates the processing of waste and includes the three waste streams household waste, bulky household waste, and construction and demolition waste. It builds on the life cycle of materials and products in the waste streams, starting with the generation of waste and ending with final processing in the form of recycling, incineration or use as refuse derived fuel, including waste collection, transportation, sorting and separation. This allows various options to be evaluated in an integrated way, while accounting for the characteristics of recycling and alternative waste processing options. Similar waste models are available, but either do not include parameters that significantly influence the results, such as transport and recycling quality (WARM, U.S. EPA, 2006), or are highly detailed life cycle assessment (LCA) tools that focus only on municipal solid waste (Easewaste, Christensen et al., 2009).

Three scenarios are considered in this study, in which the current set of policy measures ("*Successful current policy*") is compared to scenarios that focus on increased recycling ("*Recycling+*") or incineration with increased efficiency ("*Incineration+*").

The next section describes the methodology, explaining the system boundaries, the calculation of energy consumption and CO_2 emissions and the allocation of energy- and emission savings for different waste processing options. In Sections 3 and 4 the details of the selected waste streams and scenarios considered are outlined. The results and discussion are presented in Section 5, followed by the conclusions and recommendations for further research.

2. Methodology

The *i*Waste model is used to evaluate three alternative scenarios for the management of waste streams and their effects on the energy balance and CO_2 emissions. It includes data to simulate waste disposal and processing in the Netherlands in 2008 (reference situation). Parameters can be varied to test different scenarios, which can be compared with the reference situation. The model focuses exclusively on energy consumption (fuel and electricity) and CO_2 emissions and does not yet include other environmental impacts or the economics of various treatment options.

2.1. System boundaries

A schematic representation of the system boundaries is shown in Fig. 1. A careful selection of system boundaries is important in scenario analyses. Recent research by Laurijssen et al. (2010) on recycling of paper has shown that different system boundaries (i.e. taking into account resource constraints or not) can significantly influence conclusions with respect to the CO_2 emissions mitigation potential of recycling. In this study, the system boundaries are therefore carefully and consistently determined. The system boundaries for calculating energy consumption, CO_2 emissions, and savings for the processing of various materials start at the level of waste generation and end at the level of final processing in the form of recycling, incineration in a waste-to-energy plant or use as refuse derived fuel (RDF) (e.g. in industrial processes). Processes included are waste collection, transportation, sorting and separation. Landfilling of waste is not included, as the current policy in the Netherlands is aimed at minimizing waste disposal in landfills and landfill bans exist for many materials. Material losses that occur in the various steps of waste processing are taken into account in the *i*Waste model. The avoided energy consumption and CO_2 emissions are attributed as energy- and CO_2 savings to the specific processing option.

The *i*Waste model includes specific data for the Netherlands on waste stream volumes, composition, and processes (i.e. efficiencies, energy use, CO_2 emissions, and substitution factors), of which a detailed overview can be found in Corsten et al. (2010). All weight

Table 1
Materials and products included in the *i*Waste model.

Materials and products in selected waste streams[a]			
Paper and board	Steel	Polypropylene (PP)	Cardboard drinking packages
Glass	Aluminium	Polystyrene (PS)	Wood
Textiles	Copper	Polyethylene terephthalate (PET)	Mineral materials
Organic wastes	Polyethylene (PE)	Polyvinylchloride (PVC)	Roof waste

[a] Materials and products in the waste streams that are not taken into account in the study include chemical waste, tires, and other types of plastics (e.g. ABS).

is reported in metric tonnes (t). Waste processing is modelled on a material basis, with the energy consumption and CO_2 emissions for waste processing linked. Subsequently, for each of the materials in the waste streams, the contribution to total energy consumption and CO_2 emissions of waste management in the Netherlands can be mapped. The model distinguishes the materials that comprise the majority of waste produced in the Netherlands, as given in Table 1.

2.2. Energy calculations

The primary energy consumed for the production of a material is captured in the Gross Energy Requirement (GER). This GER-value indicates the energy content of a product and is linked to the technologies and specific conditions used to manufacture the product. In this study, the GER is used for calculating the avoided energy consumption and CO_2 emissions resulting from replacement of a product or raw material by reuse and recycling of materials recovered from the waste streams. The second order GER-value is used, which corrects for the energy needed to produce and transport primary energy carriers (Worrell et al., 1994). To determine the energy effects of waste processing, the analysis focuses on raw materials and intermediate goods.

2.3. Emission calculations

The CO_2 emissions resulting from waste processing in the Netherlands are calculated based on the CO_2 emission factors of the fuels consumed in the process (IEA, 2008). Following IPCC guidelines, the net CO_2 emissions from biomass are considered to be equal to zero, i.e. assuming sustainable biomass supply.

Both direct and indirect CO_2 emissions from waste processing are taken into account. Direct emissions are produced by using fossil fuels and raw materials within the system boundaries. Indirect emissions include emissions from electricity generation, where the generation occurs outside the system boundaries, but the electricity is consumed within the system boundaries. The sum of direct and indirect emissions provides the total GHG emission impact of waste processing.

The CO_2 emissions from electricity consumed by waste processing and primary and secondary material production is calculated using the average Dutch efficiency and fuel mix for electricity generation, though some of the waste processing and material production may occur outside the Netherlands. The Dutch efficiency of electricity generation is 2.26 kWh_p/kWh_e (average efficiency 44%) with a CO_2 emission intensity of 510 gCO_2/kWh_e (IEA, 2007). Heat is assumed to be produced in a gas-fired boiler with an efficiency of 90%.

The CO_2 emissions from waste incineration are calculated on a material basis. Waste used as refuse derived fuel is assumed to be used in the cement industry. The fossil fuels that are replaced are calculated based on the caloric value of the waste. An average CO_2 intensity of the cement industry in Europe (90 $kgCO_2/GJ$) is used to calculate the avoided emissions (Öko Institut and Ecofys, 2008).

2.4. Allocation of energy and emission savings

Waste processing is energetically a complex process in which choices for allocation of energy- and environmental benefits have to be determined to assign energy- and CO_2 emission savings to recycling. For reuse and recycling, this study takes the approach that the energy consumption and (related) CO_2 emissions are avoided, which otherwise would have been consumed and produced in the production of the product from primary materials. The calculations take only one lifecycle into account, though some materials can be recycled multiple times with limited loss of quality.

For recycling, a distinction is made between high- and low(er)-quality recycling. It is assumed that high-quality recycling results in replacing (part of) the primary product or material by reused or recycled materials. Alternatively, the recycled material may replace a different material, which is considered low-quality recycling. In the latter case, the GER-values of the replaced materials are used. This type of recycling is generally referred to as downcycling, as the use of the material or product is often of a lower quality and functionality than when the original primary material is replaced. The definitions used in this study for high- and low-quality recycling and the material it is assumed to substitute are presented in Table 2.

When materials are processed in a waste incinerator they are converted to energy. In waste incinerators with energy recovery, waste-to-energy plants, the generation of electricity from waste is assumed to replace generation by conventional power plants. The same is assumed for electricity generated from biogas, which is produced during anaerobic digestion of organic waste. The average efficiency of the Dutch waste incinerators in 2008 is estimated to be 21% electric and 7% thermal (LHV) (Benner et al., 2007; CBS, 2009). The European average is much lower with electric efficiencies of about 14% (Reimann, 2009). For biogas, a biogas-to-electricity efficiency of 35% is assumed (IVAM, 2008).

3. Waste streams in the Netherlands

3.1. Household waste

Household waste includes municipal solid waste (MSW) from private households. This category excludes waste water and bulky waste components, such as refrigerators, carpet, and furniture, which are part of the bulky MSW (described below).

In 2008, various fractions of household waste were separately collected for reuse and recycling. The largest separately collected fractions include paper and board, organic waste, and glass. A mixed fraction of household waste remains after the various material fractions have been separated by the consumer. The volumes of the separately collected material fractions and the mixed waste fraction from Dutch households are shown in Table 3. The composition of the mixed household waste collected in 2008, corrected for the moisture content of MSW, is shown in Table 4.

Separately collected household waste is mainly recycled. Rejected fractions and contaminants are usually incinerated or used as RDF. In 2008, 23% of the mixed household waste was sorted after collection, 75% was directly incinerated, and 2% was

Table 2
Definition of high- and low-quality recycling for the materials and products included in *i*Waste.

Material	High-quality recycling	Substituted material	Low(er)-quality recycling	Substituted material
Paper and board	De-inked paper	Paper produced from wood[a]	Not de-inked paper	Paper produced from wood[a]
Textiles	Reuse of textile products	New textile products with a substitution factor of 0.5	–	–
Steel	Recovery before incineration and used in the basic oxygen furnace	Primary steel	Recovery after incineration[b] and used in basic oxygen furnace	Primary steel
Aluminium	Production of secondary aluminium	Primary aluminium	–	–
Copper	Production of secondary copper	Primary copper	–	–
Plastics; PP, PE, PS, PVC	Plastics; PP, PE, PS, PVC	Primary plastics (1-to-1 ratio)	Production of roadside posts	Hardwood roadside posts (wood/plastic ratio 0.43)
PET	Bottle-to-bottle recycling (1/3) and bottle-to-fibre (2/3)	1/3 primary PET bottles, 2/3 PET fibres	Production of roadside posts	Hardwood roadside posts (wood/plastic ratio 0.43)
Organic wastes	Anaerobic digestion	Fertilizer and energy	Composting[c]	Fertilizer
Cardboard drinking packages	Recycling of paper and use of aluminium/plastic fraction as RDF	Paper produced from wood[a]	–	–
Mineral materials	Production of recycled granules (from only concrete rubble)	Gravel/sand and cement in concrete	Production of recycled granules	Gravel/sand
Roof waste	Production of asphalt substitute	Bitumen in asphalt	–	–

[a] The wood that is substituted by paper recycling is assumed to be used as energy source, replacing fossil energy sources (Laurijssen et al., 2010).

[b] Incineration of steel results in an average increase in oxide formation of 16% (Lopez-Delgado et al., 2003; Tayibi et al., 2007).

[c] Methane emissions (CH_4) from composting are assumed to be zero, as there seems to be no consensus on the CH_4 emissions from composting in the literature. Boldrin et al. (2009) give an overview of the CH_4 emissions from composting reported in various literature studies and report a range of 0.02–6.8 kgCH_4 per tonne of organic waste, depending on technology, input, and process management. Other studies assume that no CH_4 emissions occur when the composting process is properly managed (U.S. EPA, 2006; Cabaraban et al., 2008). Also for carbon storage resulting from the application of compost to the soil, large data ranges exist in the literature (2–270 kgCO_2eq/tonne organic waste) and is therefore not taken into account in this study (Boldrin et al., 2009; U.S. EPA, 2006; ICF Consulting, 2005).

Table 3
Volumes of separately collected fractions of household waste in the Netherlands in 2008 (CBS, 2009).

Waste fractions	Volume (kt)
Mixed MSW	3932
Organic wastes	1300
Recovered paper and board	1240[a]
Glass containers	346
Textiles	70
PET (bottle deposit system)	25[b]
Hazardous wastes	21[c]
Metal packaging	2[c]
Cardboard drinking packages	3[a]
Plastics	3[d]
Total household waste	6942

[a] PRN (2009a).

[b] Noordhoek (2009).

[c] Waste fraction not included in the analysis.

[d] KplusV (2008).

Table 4
Composition of the mixed MSW from Dutch households (SenterNovem, 2009a).

Material	Share (%mass)	Volume[a] (kt)
Organic waste	31	1187
Paper and cardboard	25.9	772[b]
Plastics	19	652[c]
Glass	4.7	185
Ferrous metals	3.1	122
Non-ferrous metals	1	38
Textiles	3.9	153
Cardboard drinking packages	3.1	65[d]
Other	8.2	329

[a] Note that the volumes of the individual materials do not add up to the 3932 kt presented in Table 3. This is because the values for paper and cardboard and plastics are corrected for moisture and contamination (see footnotes b and c).

[b] This value is corrected for the moisture content of paper and cardboard in integral collected MSW (38.8%) and corresponds to air dry paper (PRN, 2010).

[c] Excludes contamination and remaining liquids.

[d] Based on PRN (2009a), CBS (2009) and SenterNovem (2009a).

landfilled[1] (CBS, 2009). Two of the in total eleven waste incinerators in the Netherlands sort the household waste after collection. Mainly metals are recovered in this sorting step and the residue is subsequently incinerated[2].

3.2. *Bulky municipal solid waste*

Bulky municipal solid waste (bulky MSW) includes the larger waste components from private households, such as refrigerators, carpets, furniture, garden waste and other bulky items. Besides the various separately collected waste fractions of bulky MSW, there is currently still a fraction of mixed bulky household waste generated. The estimated volumes of the collected fractions of bulky MSW are shown in Table 5.

The separately collected fractions of bulky MSW are primarily recycled or reused. Little is known about the material composition of the mixed fraction of bulky municipal solid waste. One of the Dutch waste processors (AVU) studied the material composition of mixed bulky municipal solid waste in one of the provinces in the

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[1] The composition of the 2% household waste that was landfilled in 2008 is unknown. For this reason, it is assumed that all mixed household waste is incinerated, except for the amount of metals recovered after collection in two incinerators.

[2] According to SenterNovem and VA (2009), about 1454 kt of sorting residues were produced in 2008, of which 40% was landfilled and 60% incinerated. This amount of sorting residues does not exclusively consist of household waste, but includes also bulky household wastes and industrial wastes. Because the specific processing of household waste is unknown, it is assumed that all sorting residues from household waste were incinerated.

Table 5
Fractions and volumes of bulky municipal solid waste collected in 2008 (CBS, 2009).

Waste fractions	Volume (kt)
Mixed bulky MSW	672
Carpets and floor covering	13
Appliances	81
Bulky garden wastes	434
Furniture	40
Glass (windows)	9
Metals	83
Wood	384[a]
Clean demolition wastes	444
Asbestos-containing wastes	13[b]
Tires	3[b]
Clean soil/dirt	111
Bituminous roofing	11
Others	58[b]
Total bulky MSW	2356

[a] Leek et al. (2009).
[b] Waste fractions not included in the analysis.

Table 6
Fractions sorted from mixed construction and demolition waste (SenterNovem, 2009b).

Waste fractions	Volume in 2007 (kt)
Wood (A + B quality)	390
Wood (C-quality and processed)	20
Metals	70
Paper and board	20
Plastics	10
RDF	30
Rubble	950
Sand	320
Gypsum	30
Monostreams	20
Roofing materials	20
Shipped for further processing (domestically)	90
Shipped for further processing (export)	230
Residue landfilled	230
Residue incinerated	230

Netherlands in 2009. A number of truckloads were removed, shredded and sorted by material. This study uses the result of the AVU study to disaggregate the mixed bulky waste stream to different materials. However, due to the limited sample size and the samples being taken at a specific moment in the year, it is unclear to what extent the results of the AVU study represent the actual composition of total mixed bulky MSW generated in the Netherlands in 2008.

The collected mixed bulky MSW is partly directly incinerated and partly sorted. To understand what materials can be usefully sorted from the mixed bulky MSW, several sorting tests were done (e.g. by Baetsen and Afvalverwerking Rijnmond), where various material fractions were sorted for recycling or used as alternative fuel (RDF). Besides the results of these sorting tests, no information is available on the quantity and type of materials sorted from the mixed bulky MSW on a national level. The only information available is that about 73% of mixed bulky MSW was recovered in 2006, where recovery refers to both recycling and incineration with energy recovery (SenterNovem, 2008). In the same year, almost 10% (202 kt) of total bulky MSW was landfilled, although for 2008 a significant lower volume is reported (82 kt) (SenterNovem, 2008; SenterNovem and VA, 2009). In addition, about 580 kt of sorting residues were landfilled in 2008, which includes bulky MSW, but also household waste and industrial waste (SenterNovem and VA, 2009). Since it is unclear how mixed bulky MSW was processed in 2008, this study assumes that 60% of mixed bulky MSW is incinerated, and 40% landfilled.

3.3. Construction and demolition waste

Construction and demolition waste (CDW) includes all waste generated by construction, renovation, and demolition of buildings, structures and roads. About 26 Mt of construction and demolition waste was generated in the Netherlands in 2007, including 19.7 Mt of broken rubble, 4 Mt of stone-like material, and 2.6 Mt of mixed construction and demolition wastes (SenterNovem, 2009b).

Construction and demolition waste mainly consists of stone-like material that is broken by rubble crushers. A mixed construction and demolition waste stream is sorted in sorting plants, where materials are separated for recycling. Some types of construction and demolition waste (e.g. metals) are not, or only to a limited extent, found in the mixed waste stream, as demolition companies pass them directly to recyclers. These materials are therefore generally not recovered by sorting companies from the mixed construction and demolition waste.

The production of construction and demolition waste is reported biannually in a monitoring report. The monitoring report for 2006–2007 indicates, however, major differences between the results of the sorting tests and the data of the Dutch national waste reporting centre (Landelijk Meldpunt Afvalstoffen, LMA) (SenterNovem, 2009b). The monitoring report points out that one of the weaknesses is the response to the survey, which is only 8.6%. However, data from LMA do not correspond with data from other sources for a number of wastes (e.g. roofing wastes). As no more reliable data is available, the sorting results from the monitoring report of 2006–2007 are used, presented in Table 6.

Rubble and stone-like material, processed by crushers in 2007, were almost entirely reused, mainly for foundations and embankments (85%). The materials that were sorted from the mixed construction and demolition waste stream were also mainly reused and recycled. However, after sorting of the mixed stream, various residual flows remain (totally 780 kt), which are incinerated, landfilled, or further sorted. The composition of these residual flows is unknown and it is unclear whether it contains materials that may be reused or recycled. Besides the reuse and recycling of materials, there is still construction and demolition waste directly landfilled. Data from SenterNovem and VA (2009) show that in 2008 a total of 300 kt construction and demolition waste was landfilled (including material from crushers and sorting plants). Around 60% of this waste consists of roofing waste (referred to as hazardous roofing waste), 3% wood (hazardous waste), 8% sieve and crusher sand, and 29% other wastes. The composition of the “other wastes” category is unknown and it is unclear whether recyclable materials have been landfilled incorrectly. This category is therefore excluded from this study.

4. Scenarios

To assess the energy and CO_2 emission reduction potentials from waste management in the Netherlands, three scenarios are developed in this study: *Recycling+*, *Incineration+* and *Successful current policy*. These scenarios are based on the 2008 reference situation. Detailed descriptions of the assumptions made are reported by Corsten et al. (2010).

4.1. Recycling+

In the *Recycling+* scenario, more materials from the household waste, bulky MSW and construction and demolition waste are reused or recycled, with a focus on high-quality recycling. Consequently, the quantity and composition of the residual waste stream

Table 7
LAP2 recovery targets for separately collected waste streams (VROM, 2010).

Material	LAP2 target
Paper and board	75%[a]
Glass	90%
Organic wastes	55%
Plastics	42%
Textiles	50%

[a] Equals 85% of recyclable paper and board, as not all paper types are recyclable (e.g. sanitary paper, diapers, wallpaper, books) (PRN, 2009b).

that is incinerated is changed. Data show that in the reference situation (2008) a large quantity of recyclable materials remain in the residual household waste and bulky MSW that is incinerated. More reuse and recycling of materials from household waste means that separate collection is needed to guarantee high-quality material for recycling. For bulky MSW and construction and demolition waste improved sorting will allow selecting materials for high-quality recycling. The materials separately collected in the reference situation, but subsequently used for low-quality recycling, were assumed to be recycled at a quality as high as possible in the *Recycling*+ scenario. An example is the anaerobic digestion of organic waste instead of composting. Digestion produces, next to a useful product, also biogas that can be used for electricity generation. In addition, in the *Recycling*+ scenario, no municipal solid waste is landfilled and the minimum processing is incineration.

4.2. Incineration+

In the *Incineration*+ scenario, the same quantity and composition of waste is incinerated as in the 2008 reference situation. In this scenario, an incinerator with a higher electrical efficiency than the average Dutch incinerator efficiency is assumed. In this way, a larger share of the energy content of the materials is recovered in the form of energy (i.e. electricity and heat). The Waste and Energy Company (AEB) in Amsterdam has demonstrated a net electrical efficiency of 30%, of which 2% of the energy is generated by the co-located sewage treatment plant. The gross electricity generation is around 34%, where self-consumption of the waste treatment plant is 3–4% of their total electricity production (IPPC, 2006; AEB, 2006). Based on the efficiency of AEB, a net electrical efficiency of 28% (LHV) and thermal efficiency of 9.3% (LHV) is assumed for the high efficiency incinerator in the *Incineration*+ scenario.

4.3. Successful current policy

The scenario *Successful current policy* is based on a successful implementation of waste policy described in the National Waste Management Plan (LAP) (VROM, 2010). The LAP2 lists minimum standards for waste processing and its main objective is to recover more waste. The recovery methods included in LAP2 are reuse, recycling, and incineration with energy recovery (R1). In this study, the scenario *Successful current policy* focuses only on reuse and recycling as form of recovery and does not regard incineration with R1 status as recovery. The *Successful current policy* scenario can therefore be regarded as optimistic with respect to energy and GHG emissions results.

The targets in LAP2 for separately collected waste are included in the *Successful current policy* scenario and, shown in Table 7. The target for separate collection of plastics was later added and set at 42% for 2012. For many of the waste streams included in this study, incineration is the minimum standard of processing and thus can no longer be landfilled.

5. Results

The exploratory analysis of waste processing using the *i*Waste model shows that current waste management in the Netherlands already saves energy and CO_2 emissions compared to a situation where waste is not recycled or incinerated. In the 2008 reference situation, waste processing contributes to a substantial reduction in energy use by over 106 PJ and a reduction of 4.5 $MtCO_2$ emissions per year. About 70% of the energy savings are due to current recycling processes and 30% due to incineration with energy recovery. The currently mitigated CO_2 emissions are solely due to recycling and use of wastes as RDF. The incineration of waste creates additional CO_2 emissions, despite the avoided emissions in electricity generation, which is a result of the large volume of plastics in the waste and the relatively low efficiency of waste incinerators with energy recovery.

When recycling of selected materials from the waste stream is increased, this can result in additional emission reductions of 2.3 $MtCO_2$ annually, compared to the reference situation in 2008. This is equivalent to a potential improvement of more than 45%. Figs. 2 and 3 depict the results for the three scenarios. The main contributors to the CO_2 emission reduction potential are found in the optimization of the recycling of plastic (PET, PE/PP), textiles, paper, and organic waste.

5.1. Plastic waste recycling

In the reference situation, plastic waste from households is hardly recycled. The volume of the stream (approximately 650 kt/year) combined with the high energy content of plastics make it an important potential factor to achieve further energy savings and emission reductions. The largest gains can be achieved by focusing on high-quality recycling, where the virgin plastic is substituted as efficiently as possible. Low-quality plastic recycling does not replace virgin plastic, but generally replaces materials with a lower energy content (e.g. wood, concrete), and has generally low or no benefits in terms of energy and climate. Low-quality recycling of plastics and relatively large transport distances, as part of the plastic waste recycling takes place outside the Netherlands (an average transport distance of 300 km is assumed), are the reasons for the results in the *Successful current policy* scenario. In this scenario, plastic waste recycling does not result in energy savings, but will consume even more energy than in the reference situation. In the *Recycling*+ scenario the focus is on high-quality plastic recycling, recovering around 5.7 PJ of energy and resulting in an emission reduction of almost 1.4 $MtCO_2$ compared to the reference situation.

High-quality recycling makes it necessary to guarantee a clean recovered plastic flow (i.e. high purity of the different polymer fractions). From a theoretical point of view it can be concluded that any form of separation from complex waste streams will lead to a certain degree of contamination (Gutowski et al., 2008). This means that plastic waste collection should preferably target consumer sorting of specific polymers that can be collected efficiently and effectively with a high degree of purity. The collection of PET bottles through a deposit system is an example of such a system. In the *Recycling*+ scenario it is assumed that the PET and PE/PP bottles and bags can be collected effectively, while for other plastic streams no high-quality recycling is assumed.

5.2. Textile reuse and recycling

Textile reuse and recycling provide additional potential for saving energy and CO_2 emissions. Both the household and the bulky household waste still contain a large amount of textile fabrics. For textiles it is difficult to determine the amount of resources saved

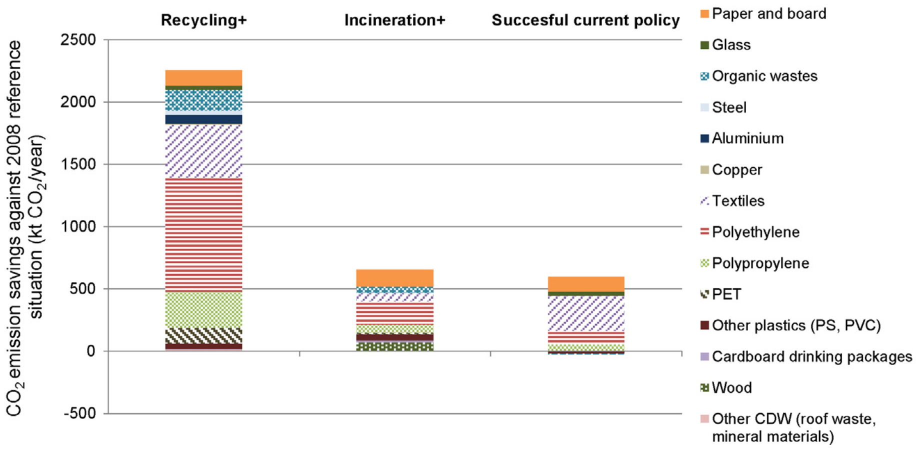

Fig. 2. CO_2 emission reduction potentials of the *Recycling+*, *Incineration+* and *Successful current policy* scenarios for waste management in the Netherlands in 2008. The figure shows the additional impact of the scenarios to the 2008 reference situation.

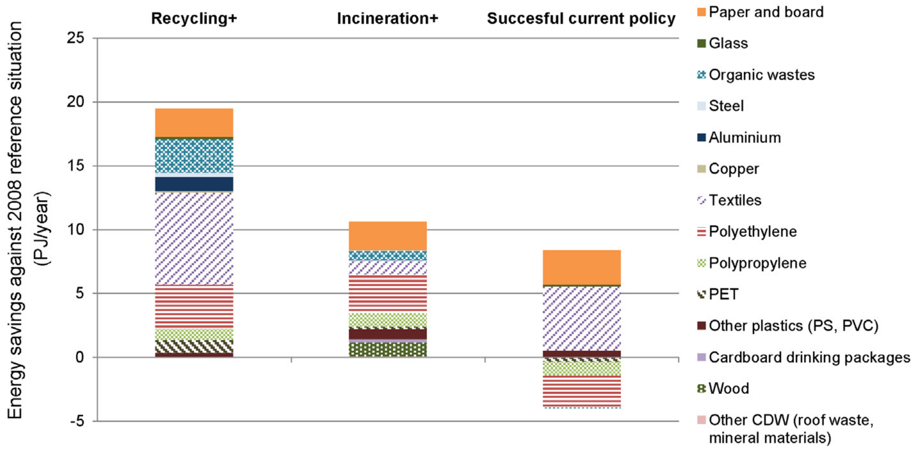

Fig. 3. Energy savings potentials of the *Recycling+*, *Incineration+* and *Successful current policy* scenarios for waste management in the Netherlands in 2008. The figure shows the additional impact of the scenarios to the 2008 reference situation.

due to reuse and recycling. Clothing causes an even bigger problem, as a recycled garment does not always replace a new piece of clothing (Woolridge et al., 2006). For this reason, a substitution factor of 0.5 is used for clothing. This assumes that the primary material lives twice as long as the secondary material (Prognos, 2008). Separate collection and processing of high-quality textile wastes can contribute significantly to reduce the energy consumption and associated CO_2 emissions (470 ktCO_2/year). The largest contribution (about 90%) of the potential emission reduction is due to increased reuse of clothing. Carpet recycling is possible, but has not been included in the current calculations.

5.3. *Organic waste recycling*

Anaerobic digestion can result in significant energy savings compared to composting. At present only 7% of the separately collected wet organic waste and biomass from households is digested. Composting contributes to a better nutrient balance, but does not add to energy- and GHG emission reductions. However, fermentation can significantly contribute to the recovery of energy, while retaining the nutrients. In the *Recycling+* scenario it is assumed that all separately collected organic waste (75% of total volume) is fermented in anaerobic digestion units, resulting in an energy production of 3.7 PJ (460 GWh). As a result, this amount of energy is saved and emissions equal to 235 ktCO_2/year are reduced from conventional electricity generation. This leads to a net emission reduction of more than 160 ktCO_2/year for the processing of organic wastes compared to the reference situation. Because municipal pruning and garden waste is not included in this study, there is additional savings potential for organic waste processing. The realization of this energy gain can only be achieved with significant investments in digestion plants throughout the Netherlands.

5.4. *Paper recycling*

Paper is already largely recovered through various collection systems. In 2008, 62%[3] of household paper waste was collected separately. Paper recycling leads to potential large savings in energy use and CO_2 emissions, because it frees up wood as energy source replacing fossil fuels (Laurijssen et al., 2010). But the success of separate paper collection can be further improved. Currently more paper is collected from commercial buildings than from households. Increasing the collection efficiency of paper from households to 75% can contribute to energy savings of 2.1 PJ and an emission reduction of 115 ktCO_2. The higher the required quality, the more fibres are lost during the paper recycling process. Therefore, for efficient processing, it is essential that the collected paper is free from contamination of food and other organic wastes. For high-quality

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[3] This corresponds to about 74% of recyclable paper, as not all types of household paper waste can be recycled.

recycling (de-inked paper) about 12% of fibres are lost (Laurijssen et al., 2010). Cardboard drinking packages are a potential additional source of paper fibres, but have to be processed separately from the flow of paper to prevent contamination.

5.5. Metal recycling

Improved recycling of metals can contribute to a reduction in energy use and CO_2 emissions. Metals (mainly iron and steel) are already largely recovered with a high efficiency, although only 20% of aluminium is recovered from the waste. The *Recycling*+ scenario indicates a potential energy saving of 1.6 PJ and a 110 ktCO$_2$ emission reduction through improved collection and recovery of metals from household waste including separate collection of part of the aluminium packaging.

5.6. Incineration

Incineration has a role in waste management and in each scenario part of the waste is still incinerated. The quantity and composition of waste incinerated varies in each scenario with the degree of waste materials sent for recycling or used as RDF. A scenario which assumes a high energy conversion efficiency of the incinerator (*Incineration*+), treating residual waste streams, achieves an emission reduction equivalent to only one third of the reduction of the *Recycling*+ scenario. This indicates that high-quality recycling or reuse of recovered materials is preferred over incineration, even if the incinerator has an increased efficiency.

5.7. Current and future policy approach

The results show that initiated policy only partially realizes the potential energy savings and CO_2 emission reduction identified for the Netherlands. In LAP2, the government sets minimum targets for each waste stream and this study assumes the LAP2 objectives will actually be realized. The results show that, if current initiated policy would be successful, annually 4% more energy (equivalent to 4.4 PJ) and almost 15% more CO_2 emissions (equivalent to 575 ktCO$_2$) can be avoided compared to the reference situation in 2008. The present targets alone will thus not secure full take up of the latent potential to save energy and CO_2 emissions. An integrated approach of all waste streams, focusing on the highest quality use of recovered materials, is essential to realize the full potential energy savings and CO_2 emission reduction identified in this study. Compared to the current policy, the largest potentials are for plastics, textiles and organic waste.

6. Conclusions

The study shows that there is still a large potential for further improvement of waste management in the Netherlands. Especially in a scenario where the focus is on product and material reuse and (high-quality) recycling (*Recycling*+), large potential savings (2.3 MtCO$_2$ and 19 PJ) are identified. The materials that will play an important role in achieving the full savings potential are plastics (PET, PE and PP), textiles, paper, and organic waste. A scenario focusing on incineration with a higher energy conversion efficiency (*Incineration*+) has the potential of only saving one third of the CO_2 emission savings achieved in the *Recycling*+ scenario. The results also confirm that, in terms of energy consumption and CO_2 emission reduction, the waste hierarchy that is used as the basis for European waste management policy, is still valid in prioritizing waste disposal options, but only when a clear distinction is made between high- and low-quality recycling. These different qualities of recycling should be consequently taken into account when designing (national) waste management policy. Therefore, to achieve the full potential energy savings and CO_2 emission reductions identified in this study, a comprehensive and integrated waste management policy is necessary, which should give priority to high-quality recycling. This is best achieved with a menu of policy instruments, accounting for the specific characteristics of a waste stream and recycled materials markets. Detailed economic and technical analyses of high quality recycling are recommended to further evaluate viable integrated waste management policies. Furthermore, more detailed analyses of selected waste and material flows are necessary, as well as research on innovation and development of waste treatment and recycling technology.

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