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Plastic pathways

Recycling routes, results and recommendations

Contacts

The Netherlands
Dr. Paul Nillesen
Partner, Strategy& Netherlands
+31-6100-38-714
paul.nillesen@pwc.com

Rutger Bots
Manager, Strategy& Netherlands
+31-6102-71-949
rutger.bots@pwc.com

About the authors

Paul Nillesen advises clients in the power, utilities, and waste industries on strategy and transactions for Strategy&, PwC's strategy consulting business. He leads the Netherlands Energy, Utilities & Resources Industry Practice and is part of the global Energy leadership team for PwC. Based in Amsterdam, he is a partner with Strategy& Netherlands.

Rutger Bots advises clients in the power, utilities, and waste industries for PwC Strategy&. He specializes in strategy development, market assessments, business case modeling and organizational transformations. Based in Amsterdam, he is a Manager with Strategy& Netherlands.

Jim Baarslag advises clients in the power, utilities, and waste industries for PwC Strategy&. He specializes in strategy development, market research and modeling. Jim has a background in Economics and Physics. Based in Amsterdam, he is a Senior Associate with Strategy& Netherlands.

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Any remaining errors are those of the authors.

KEY INSIGHTS

- Between 32–35 percent of all household plastic waste is recycled into usable secondary raw materials, depending on the chosen recycling pathway.
- There are currently two plausible plastic recycling pathways for stakeholders to consider: source-separation (households do most of the work) or post-separation (machines do the work). The choice depends on specific circumstances, such as urban complexity, costs and technological developments, and policy preferences by stakeholders.
- A detailed cost assessment reveals that the costs per pathway do not differ significantly and as such provide no knock-out argument for choosing between the two pathways: source-separation costs between 1,036 and 1,138 Euro per ton of plastic waste while post-separation costs 1,163 Euro per ton of plastic waste.
- Carbon abatement costs of all the recycling pathways are high compared to current carbon prices (more than 250 Euro per ton of CO_2 avoided).
- Post-separation is likely to gain ground as a result of technological progress which will increase recycling yields; economies of scale lowering investment and operational costs; and the post-separation of other valuable waste streams (e.g. paper/cardboard) together with plastic (sharing the costs across multiple waste streams).
- Of the three steps in the process (separation, sorting, and recycling), improving the recycling yield will have the largest impact on overall results and overall recycling rates. The focus here should be on incentivising the use of more attractive plastics versus unattractive plastics in terms of recyclability.
- Improving the attractiveness of using recycled plastic (and increasing the price as a result) will drive down relative costs and help close the material loop.

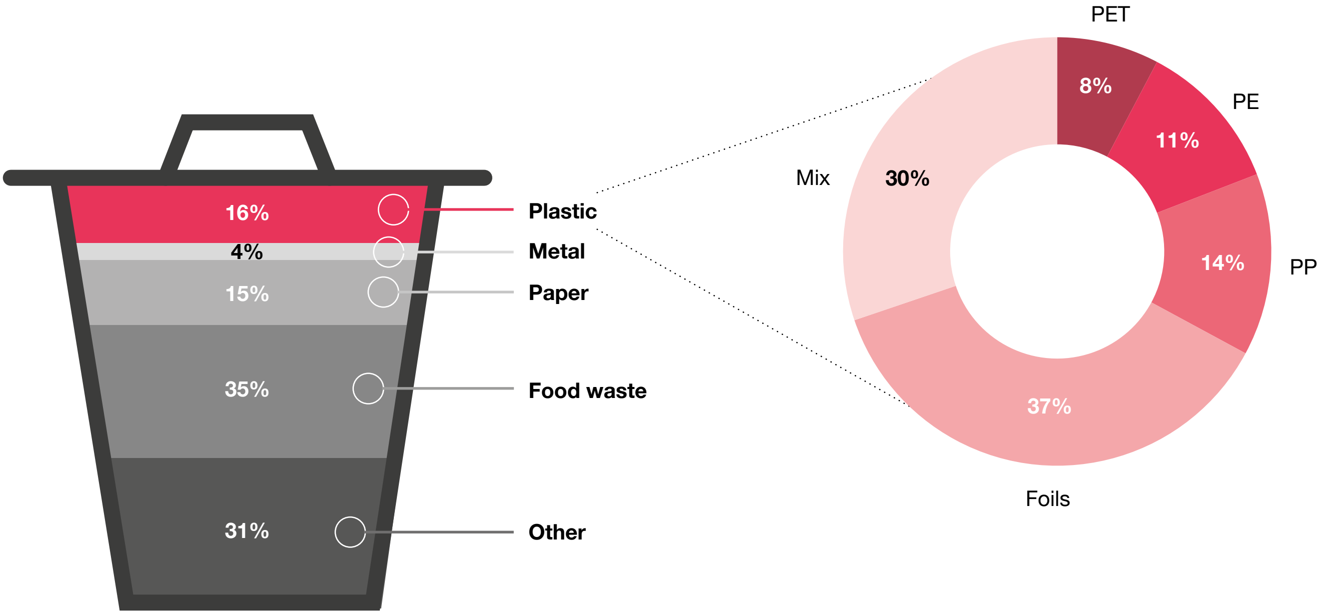
INTRODUCTION

Minimising the use of virgin plastics and maximising the recycling rate of used plastics is a key focus area in current waste policy. The Netherlands has developed policies and incentives to increase the recycling rate of plastic waste to meet (and exceed) European targets. Household plastic waste makes up around 16 percent of municipal solid waste and splits out into different plastic types, such as PET, PE, PP (*see Exhibit 1*). There are different pathways for recycling plastic waste, some of which have been analysed in the past.[1] However, a comprehensive study that compares all the main pathways for plastic waste from collection to recycled plastic feedstock has not been undertaken so far.

In this paper we analyse the five main plastic waste pathways and compare them in terms of recycling performance, economic costs, and carbon emissions. The objective of our study is to provide a like-for-like comparison, without drawing conclusions on the "best" pathway. We identify the levers that stakeholders can influence to bring down costs, increase efficiency, and reduce environmental impact. Our model is tailored to the Dutch situation but is fully flexible, allowing all parameters to be adjusted to country-specific situations, to test policy initiatives, or to assess the impact of efficiency improvements.

1 See for example R. Gradus et al. (2017) for a comparison of incineration versus source-separation.

EXHIBIT 1
Composition of Dutch municipal solid waste[1]



1 We express plastic composition in terms of separation output (i.e. including a mix component); with all 2D fractions grouped as Foils; and 3D fractions as PP, PE and PET. In addition, we make no distinction between packaging and non-packaging plastics.
Source: Strategy& analysis

Plastic pathways

We have modelled the five most common plastic waste pathways, except for mismanaged plastic waste (litter) and deposit systems[2] (*see Exhibit 2*).

The most straightforward, and common, routes are landfill or incineration (waste-to-energy) of plastic waste. Incineration allows for energy to be recovered from the plastic waste and used for power generation or heat.[3] Landfill essentially avoids carbon emissions from incineration of plastic waste, but is not considered as recycling (and causes high amounts of methane emissions, offsetting the benefits from lower carbon emissions).

Other routes are more complex. In the source-separation route, households manually separate plastic waste at home, which is then collected separately. Source-separation rates vary substantially between municipalities and even between neighbourhoods, driven by differences in inner-city complexity, service levels and financial incentives (e.g. differentiated tariffs based on weight or other factors). As there is a significant difference in separation rates between municipalities, we include an urban and rural sub-pathway (we also apply this for the hybrid pathway).

2 In the Netherlands the deposit system has recently been extended to small PET plastic bottles and aluminium cans. Current data does not allow for a full comparison at this moment. We expect that the deposit system will lower the volumes of plastic waste in household waste, both for source-separation and post-separation and will thus increase per unit costs. It could further lower the value of the remaining plastic waste stream, given the relative attractiveness of PET versus other plastic waste.
3 In this study we do not consider energy recovery as a form of recycling. We are interested in the recovery and production of usable secondary material.

EXHIBIT 2
Plastic pathways

	Source-separation	Post-separation	Sorting	Recycling	W2E	Landfill
1. Landfill						✓
2. Waste-to-energy					✓	
3. Source-separation	✓		✓	✓	✓	
4. Post-separation		✓	✓	✓	✓	
5. Hybrid (source and post-separation)	✓	✓	✓	✓	✓	

Source: Strategy& analysis

In the post-separation route, machines do the work for households by applying sophisticated machinery (e.g. wind shifters or near infrared scanners) to separate the plastics from municipal solid waste.

The most complex route (the ‘hybrid’ route) combines the source- and post-separation routes to maximise material recovery. In this pathway households first separate plastic waste manually, which is then transported to a sorting facility. The remaining residual waste (with significantly less plastic waste) is then sorted by a machine.

Following the separation step (source, post, and hybrid), plastic waste is transported to a sorting facility. Here the plastic mix is sorted into different fractions (PE, PP, PET, etc.) and any non-plastics are removed. Finally, the plastic fractions are processed and recycled into secondary flakes or pellets in a recycling facility.

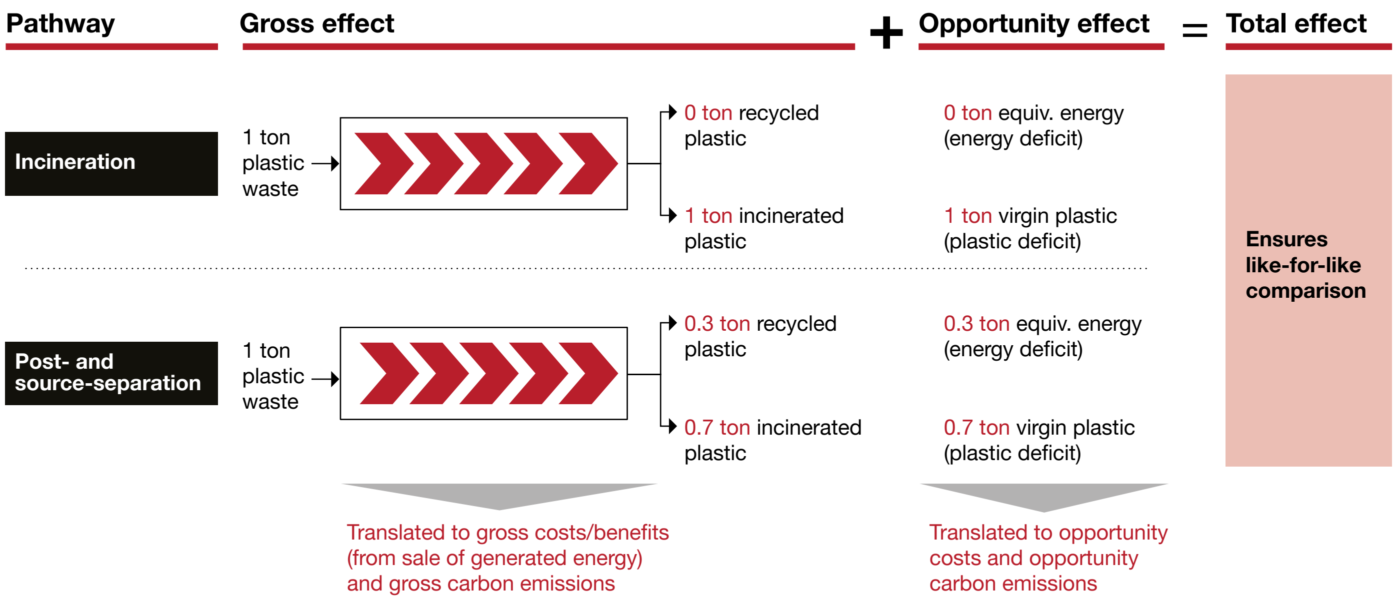
Our model captures all the steps for each plastic pathway and includes all relevant parameters, such as cost and benefit data, recovery rates, and carbon emissions.[4] By starting with the same amount of plastic waste in each pathway, we determine the recycling rate (the share of secondary flakes or pellets relative to the starting volume of plastic waste[5]), the gross costs (gross costs per ton of plastic waste and per ton of recycled plastic), and the carbon emissions (emissions per ton of plastic waste). By comparing costs with emissions abatement, we derive the shadow carbon emission price per plastic pathway.

To ensure a like-for-like comparison across the pathways, we account for the missed opportunity for recycling, in case of incineration or landfill, and missed energy recovery in case of plastic waste recycling or landfill (*as illustrated in Exhibit 3, next page)*. Where plastic is not recycled, we assume that this “plastic deficit” is replaced with virgin plastic. Similarly, for plastic that is recycled and not incinerated, we assume an “energy deficit” that is replaced by energy from the market. In both instances we include the cost and emission implications of these deficits (referred to as opportunity costs).

4 See Appendix B for an overview of all parameters and sources.
5 We define the recycling rate as the mass of usable secondary material as a share of the total plastic waste mass. Usable secondary material is compatible in terms of quality with virgin plastic. Typically, the recycling rate is defined as the mass of usable secondary material as a share of plastic waste mass offered at the start of the recycling stage.

EXHIBIT 3

Approach to ensure like-for-like comparison across pathways (numbers are illustrative)



Source: Strategy& analysis

Recycling rate per pathway

Exhibit 4 summarises the recycling rates per plastic pathway, and the intermediate steps (separation, sorting and recycling). In the case of post-separation for example, 64 percent of the plastic is separated by the machines, followed by 90 percent yield in the sorting step,[6] and a subsequent yield of 56 percent at the recycling stage. The compound yield of these three steps is then 32 percent. That is to say, 32 percent of the original plastic waste ends up as a usable secondary source for new plastic applications. Along this pathway the remaining 68 percent of the available plastic in the waste ends up incinerated (in the case of the Netherlands). This is because all three steps are not flawless and not all plastic waste is recyclable. For example, sorting losses are relatively low (mainly driven by the removal of contaminated plastic). The recycling yield, on the other hand, ranges from 40 to 80 percent. The large range in yield is due to the different types of plastic: foils and mix are at the lower end of the range, whilst PET, PE and PP are at the higher end of the range.

The source-separation yield is highly dependent on the degree of urban complexity. In rural areas the separation yield is on average 77 percent, whereas in urbanised areas this falls to 36 percent. That also affects the average compound recycling rate, with 16 percent recycling

6 The challenge for source-separation is consistent separation of high-quality plastics: source-separation can lead to high-quality plastics very suitable for recycling, but also result in low-quality plastics due to high levels of contamination. This effect is captured in the applied sorting and recycling yields.

EXHIBIT 4
Recycling rates per plastic pathway

Pathway		Average separation yield	Average sorting yield	Average recycling yield	Average recycling rate (compound)
Landfill		0%	0%	0%	**0%**
Incineration		0%	0%	0%	**0%**
Post-separation		64%	90%	56%	**32%**
Source-separation	Urban	36%	79%	57%	**16%**
	Rural	77%	79%	57%	**35%**
Hybrid (source and post)	Urban	77%	85%	57%	**37%**
	Rural	91%	82%	59%	**44%**

Source: Strategy& analysis

for urban areas and 35 percent for rural areas.[7] Post-separation averages a separation yield of 64 percent and higher sorting yields than source-separation (90 versus 79 percent). The latter is driven by the fact that post-separators are designed and optimised to separate valuable plastic waste from municipal solid waste, leading to lower losses in consecutive stages of the process. The hybrid pathway leads to the highest recycling rate (up to ~44 percent) – given both the source-separation step and the post-separation step.

Costs per pathway

Exhibit 5 summarises the total costs per ton of plastic waste per plastic pathway, split between gross costs and opportunity costs. The gross costs are those directly related to the specific pathway (e.g. operational and capital costs for the post-separation and W2E facilities, collection, and transport), excluding taxes. The opportunity costs relate to either virgin plastic material that is needed to replace plastic that is not recycled, or the deficit in energy if plastic waste is not incinerated.

7 Sorting yield averaged over all plastic fractions, i.e. including 2D fractions that are not processed in sorting stages and are thus included in this figure as being sorted at 100 percent yield.

EXHIBIT 5
Costs per plastic pathway (€ per ton plastic waste)

Pathway		Gross costs	Opportunity costs	Total costs
Landfill		121	851	**972**
Incineration		97	719	**816**
Post-separation		634	528	**1,163**
Source-separation	Urban	416	620	**1,036**
	Rural	629	508	**1,138**
Hybrid	Urban	815	495	**1,310**
	Rural	873	456	**1,330**

Source: Strategy& analysis

The hybrid route is the most expensive in terms of costs – as could be expected given that it includes both source- and post-separation steps, where the source-separation reduces the quantity of plastics in the waste that is treated in the post-separation facility, thus increasing the unit cost. The cheapest option is waste-to-energy, where costs for separation, sorting, and recycling are avoided.

The source- and post-separation routes have a similar cost profile, with source-separation having lower overall costs. The extra costs for post-separation (capital expenditure and operational costs) outweigh higher collection costs for source-separated plastic waste.[8] The higher recycling rate in post-separation also increases costs, as recycling is more expensive than incinerating plastic waste.

Most of the costs for the separation routes are driven by infrastructure costs – separation, sorting, and recycling facilities – whereas for the landfill and waste-to-energy routes most costs are driven by opportunity costs for the plastic and energy deficits resulting from landfill or incineration of plastics.

A closer review of cost components for source- versus post-separation (*see Appendix A*) shows that the main driver of cost difference is post-separation plant cost, with source-separation having no separation step costs. The post-separation costs are relatively high because the facility must process not only plastic, but also approximately five times as much non-plastic waste. Despite the high volume and mix of materials processed, most of the entire plant's cost is allocated to the plastic waste stream.

8 We exclude the implicit labour costs associated with manual separation in the source-separation step (we ignore the implicit costs of labour by households to separate their waste).

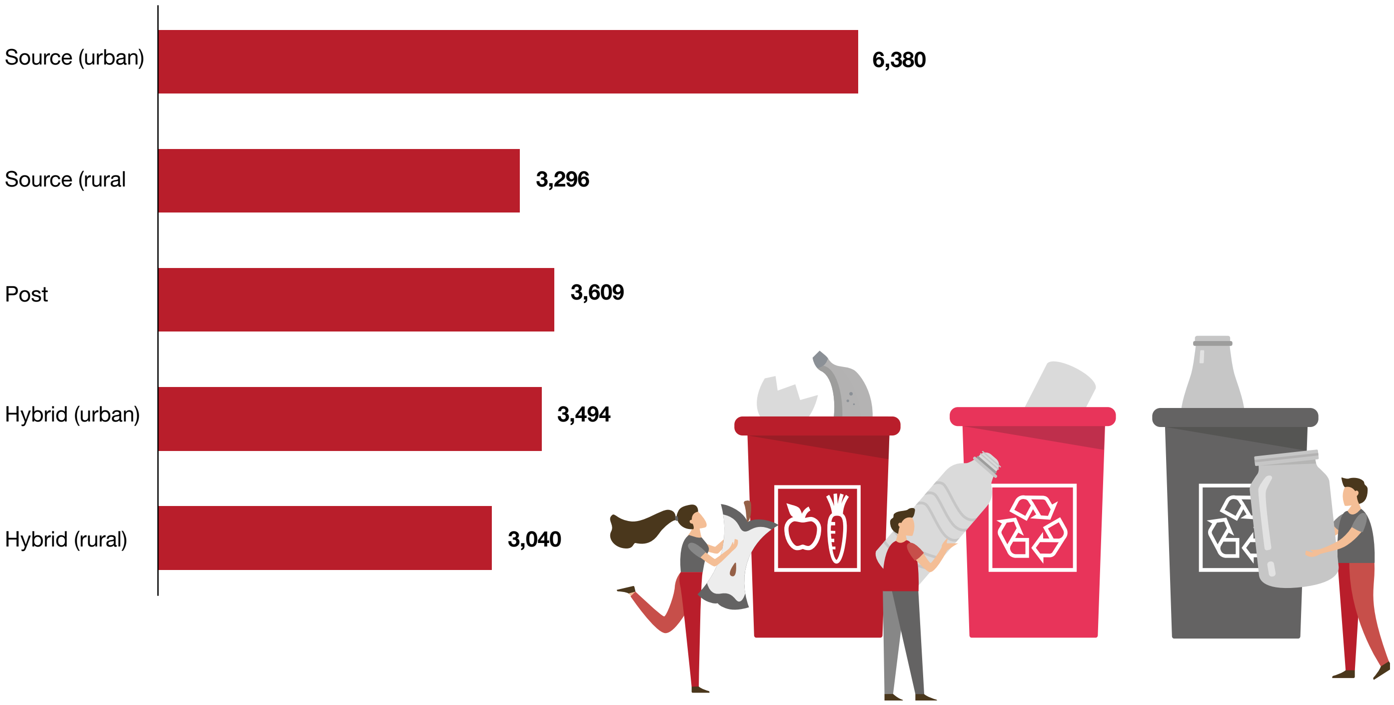
> "Between 32–35 percent of all household plastic waste is recycled into usable secondary raw materials, depending on the chosen recycling pathway."

Across routes, it is important to recognize that the recycling rate substantially influences the level of costs in each step: collecting, transporting, and processing costs are dependent on the mass of plastic at each stage in the process. As a result, while the variables that impact the recycling rate tend to be those that come early in the process (e.g. source-separation yield), these also increase the total cost within the system by increasing the amount of mass. In contrast, variables that increase the recycling rate later in the process (e.g. recycling plant recovery rate) have the same effect on the total recycling rate but lead to lower increases in total processing costs – and are thus more cost-effective in improving recycling rates.

Importantly, our cost assessment shows that the opportunity costs from not recycling are higher than the opportunity costs from recycling.

An alternative cost metric is the costs per ton of recycled plastic waste, which is relevant if the objective is to recycle as much plastic as possible at the lowest cost (contrary to simply disposing of waste at the lowest cost). This metric shows that in areas where source-separation rates can be expected to be high (e.g. typically rural areas), source-separation is more cost-efficient than post-separation; and the hybrid pathway is most efficient per ton of recycled plastic, as the increment in recycling rate of adding either source- or post-separation to the other outweighs the cost increment. For areas with low expected source-separation rates (e.g. urban areas), post-separation is significantly more efficient than source-separation; and moving from post- to hybrid separation is only a marginal improvement (*see Exhibit 6*).

EXHIBIT 6
Source- versus post-separation (€ per ton recycled plastic waste)



Source: Strategy& analysis

Carbon emissions per pathway

Exhibit 7 summarises the carbon emissions per plastic pathway, split between gross emissions (directly from the process) and emissions resulting from the opportunity cost effects (virgin plastic or energy replacement). Note that we only consider carbon emissions in this picture and exclude other greenhouse gases such as methane, which is particularly relevant for landfill (landfill seems relatively attractive, while in reality it is highly polluting). In addition, we do not consider pathways with carbon capture.

In contrast to the total cost view, carbon emissions are lowest for the hybrid pathway, followed closely by post-separation. The opportunity cost is a significant contributor to carbon emissions (near 100 percent for landfill route, 20–25 percent for others). Like costs, this opportunity cost works in two directions: firstly the emissions from creating carbon-intensive virgin plastic to replace non-recycled material, and secondly the emissions from generating alternative energy rather than plastic incineration (although the gross emissions from incineration more than offset this effect).

The largest factor influencing carbon emissions is the plastic recycling rate. A lower recycling rate has two compounding impacts: increasing the volume of plastic that is incinerated (at higher carbon emission levels than alternative energy sources) and increasing the (carbon-heavy) production of replacement virgin plastic. This factor dwarfs the impact of other factors, such as additional emissions from transporting to and processing at the post-separation plant. This explains why a hybrid route performs best when it comes to CO_2 emissions.

EXHIBIT 7
Carbon emissions (i.e. excluding other greenhouse gases) per plastic pathway (ton CO_2/ton plastic waste)

Pathway		Gross emissions	Opportunity effect	Total carbon emissions
Landfill		0.0	1.7	**1.7**
Incineration		2.9	0.9	**3.8**
Post-separation		2.1	0.6	**2.7**
Source-separation	Urban	2.5	0.7	**3.2**
	Rural	2.0	0.6	**2.6**
Hybrid	Urban	2.0	0.5	**2.5**
	Rural	1.8	0.5	**2.3**

Source: Strategy& analysis

At present, we are applying emissions from energy use at the current mix of renewable generation in the Netherlands (8 percent). If the Netherlands were to achieve the 2030 ambition of increasing the mix of renewables to 32 percent, this would reduce CO_2 emissions from plastic recycling routes by 0.2 t CO_2/t plastic processed (-6 percent), because of a reduction in the opportunity effect of alternative electricity and heat generation, as well as a reduction in the emissions from electricity used in the processing steps.

Moving to 100 percent renewable energy would reduce emissions by almost 0.3 t CO_2/t plastic processed (-8 percent). Further CO_2 reductions, which are not explored in this paper, could also be achieved by reducing carbon emissions from virgin plastic production and transport routes.

Carbon abatement prices per pathway

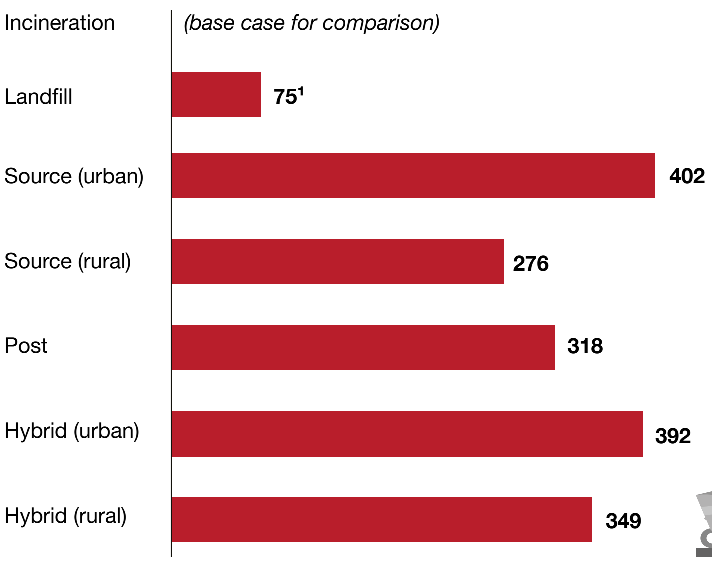
We can now combine costs and carbon emissions to calculate the carbon emission abatement costs per plastic pathway and compare this with current market prices for carbon. To calculate the abatement cost we use the incineration pathway as the baseline – given that this pathway results in the highest carbon emissions (*see Exhibit 8*).

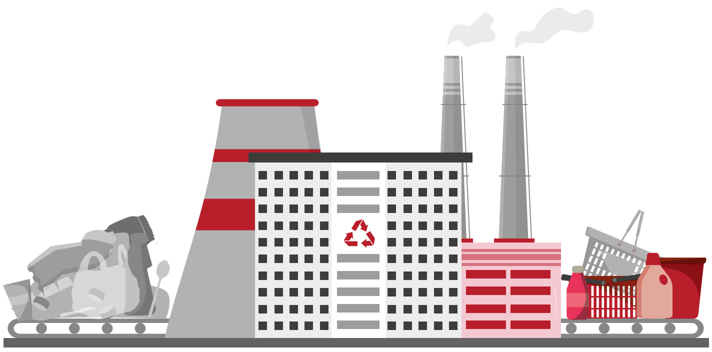
In all the recycling pathways the carbon abatement cost is far above the market price of carbon. At present all plastic recycling routes would perform poorly on a marginal abatement cost curve against alternatives receiving subsidy support (for example residential insulation).

In this analysis, landfill appears to have the lowest CO_2 abatement cost. However, although landfill avoids incineration of plastic waste and the majority of the processing steps, we ignore the relatively high amount of methane emissions associated with landfill, thus overestimating the benefits.

EXHIBIT 8

Cost of carbon abatement vs. incineration (€/ton CO_2 avoided)





1 Ignoring (high) methane emissions
Source: Strategy& analysis

Man and machine

The two main pathways for recycling plastic waste into usable secondary raw materials are source-separation and post-separation (and their combination). When deciding which pathway is most suitable, stakeholders need to consider urban complexity and projected separation yields and offset these against costs, carbon emissions and other relevant policy considerations. There is no one-size-fits-all solution, but rather a solution that is tailored to the specific situation.

In general, source-separation performs well in areas with low urban complexity (where space allows for mini-containers, for example) and when compliance rates (separation yields by households) are high. As urban complexity increases, for example in more metropolitan and high-rise areas, the possibilities for mini-containers decrease and alternative solutions, such as underground containers, become more expensive. This is where post-separation pathways become more interesting economically and environmentally.

Over time we expect that post-separation performance will improve, because of technological progress and cost reductions, which will shift the balance more in favour of this pathway versus source-separation. The extension of waste streams that can be post-separated, such as paper, glass, or other valuable materials, will further drive down unit costs from a plastic recycling perspective.

At the same time an increase in deposit-like systems, where valuable and easily recyclable materials are collected and remunerated separately, is likely to have the opposite effect on both source- and post-separation, by increasing unit costs (as both volume and quality decreases) and reducing the value of the remaining plastic waste (as the more valuable plastics have been removed). Whereas the source- and post-separation routes do not interfere with one another and can co-exist, deposit systems can affect the economics of both pathways significantly. An integral perspective is therefore necessary from stakeholders to balance the costs and the benefits. More work will need to be done to assess the exact costs and benefits of deposit-based systems in relation to existing pathways.

> “Over time we expect that post-separation performance will improve, because of technological progress and cost reductions, which will shift the balance more in favour of this pathway versus source-separation.”

Recommendations

The Dutch government has set the goal of having a circular economy in the Netherlands by 2050. Given the high cost and environmental impact of recycling plastics, the focus needs to be on reducing the overall consumption of (virgin) plastics. In parallel, the plastic pathways have multiple levers for reducing costs and improving overall recycling rates:

1. Stimulate innovation in all the processing steps for recycling plastic waste (post-separation, sorting and recycling) to increase yields. Most notably in the final recycling step, where yields are relatively low. Alternative technologies, such as chemical recycling, could be considered.

2. Post-separate other valuable waste streams (e.g. metals, paper/cardboard) by expanding the configuration of the post-separation facility. This should drive down the unit costs of processing plastic waste, as the costs of the facility will be allocated over multiple streams instead.

3. Review recyclability of (single-use) plastics and improve the recyclability of plastic in general. This can be achieved by replacing less attractive plastics with more attractive ones (e.g. PET, HDPE) and designing plastics to allow better machine recognition.

4. Consider regional conditions (incl. leveraging the existing infrastructure) when realizing a plastic recycling pathway. In general, rural areas fit source-separation, while more urban areas fit post-separation. Take household preferences and convenience into account to lower barriers for recycling.

5. Improve the attractiveness of using recycled plastic (and increasing the market price as a result) to drive down relative costs and help close the material loop. National governments can set targets for the reuse of plastic, creating and growing the market for recycled plastics.

Appendix A: Cost and emission components per recycling pathway

TABLE A1

Costs per plastic pathway (€ per ton plastic waste)

Pathway		Collection	Post-separation	Plastic sorting and recycling (ex. sales of recycled plastic)	Incineration/ landfill (ex. sales of energy)	Transport	Sales of energy	**Gross costs**	(Opp.) costs of replacing plastic (virgin production)	(Opp.) costs of 'energy loss'	**Total costs**
Landfill		91	–	–	25	5	–	**121**	719	131	**972**
Incineration		91	–	–	133	5	-131	**97**	719	–	**816**
Source	Urban	227	–	178	111	10	-110	**416**	599	21	**1,036**
	Rural	232	–	384	87	12	-86	**629**	463	45	**1,138**
Post		101	188	333	90	12	-89	**634**	486	42	**1,163**
Hybrid	Urban	234	175	390	83	15	-82	**815**	446	49	**1,310**
	Rural	234	161	464	75	14	-74	**873**	399	57	**1,330**

Note: Costs per process step are expressed in costs per total amount of plastic waste, not in costs per amount of plastic waste processed in that specific step. As such, plastic volumes processed in specific steps may drive significant cost differences for these steps between pathways.
Source: Strategy& analysis

TABLE A2

Carbon emissions per plastic pathway (ton CO_2/ton plastic waste)

Pathway		Collection[1]	Post-separation	Plastic sorting and recycling (ex. sales of recycled plastic)	Incineration/ landfill (ex. sales of energy)	Transport	**Gross emissions**	Emissions of replacing plastic (production of virgin plastic)	Avoided emissions due to energy generation (W2E)	**Total emissions incl. opportunity effect**
Landfill		–	–	–	0.01	0.00	**0.01**	**1.69**	–	**1.70**
Incineration		–	–	–	2.90	0.00	**2.91**	**1.69**	-0.82	**3.78**
Source	Urban	–	–	0.06	2.43	0.01	**2.50**	**1.42**	-0.69	**3.23**
	Rural	–	–	0.13	1.90	0.01	**2.04**	**1.11**	-0.54	**2.62**
Post		–	0.03	0.09	1.97	0.01	**2.10**	**1.15**	-0.56	**2.69**
Hybrid	Urban	–	0.03	0.12	1.82	0.01	**1.98**	**1.06**	-0.51	**2.52**
	Rural	–	0.03	0.15	1.63	0.01	**1.82**	**0.95**	-0.46	**2.31**

1 Assumed negligible (as the majority of emissions is expected to come from transport during collection, which is included in the Transport column).
Note: carbon emissions per process step are expressed in emissions per total amount of plastic waste, not in emissions per amount of plastic waste processed in that specific step As such, plastic volumes processed in specific steps may drive significant emissions differences for these steps between pathways.
Source: Strategy& analysis

TABLE A3
Comparison of key metrics based on costs and emissions per recycling pathway

Pathway		Total costs (€/ton plastic waste)	Recycling rate (ton recycled plastic/ ton plastic waste)	Total costs per ton of recycled plastic (€/ton plastic recycled)	Total emissions (ton CO_2/ ton plastic waste)	CO_2 abatement costs (€/ton CO_2 avoided vs. W2E)
Landfill		972	0%	n/a	1.7	75
Incineration		816	0%	n/a	3.8	n/a
Source	Urban	1,036	16%	6,380	3.2	402
	Rural	1,138	35%	3,296	2.6	276
Post		1,163	32%	3,609	2.7	318
Hybrid	Urban	1,310	37%	3,494	2.5	392
	Rural	1,330	44%	3,040	2.3	349

Source: Strategy& analysis

Appendix B: Summary of inputs and sources

Mass

#	Metric	Value	Source type	Detailed source
1	Composition of plastic in household waste	8% PET; 11% PE; 14% PP; 37% Foils; 30% mixed	Published paper – WUR	Verbeteropties voor de recycling van kunststofverpakkingen"; E.U. Thoden van Velzen, M.T. Brouwer en C. Picuno, Food and Biobased Research. 2018
2	% of household plastic source-separated	52%	Data – CBS	CBS waste data; average of all municipalities. Also calculated from this data: average compliance rates for urban vs. rural and differentiated tariffs vs. non differentiated tariffs
3	Composition of plastic in source separated recycling bin	8% PET; 10% PE; 12% PP; 25% Foils; 45% mixed	Published paper – WUR	Verbeteropties voor de recycling van kunststofverpakkingen"; E.U. Thoden van Velzen, M.T. Brouwer en C. Picuno, Food and Biobased Research. 2018
4	% of additional residual waste (aanhangend vuil) mixed with plastic waste (source-separation)	17%	Published paper – WUR	Verbeteropties voor de recycling van kunststofverpakkingen"; E.U. Thoden van Velzen, M.T. Brouwer en C. Picuno, Food and Biobased Research. 2018
5	Composition of processed material (post-separation)	16% plastic, 4% metal	Data – NSI	NSI data
6	% recovery rate post-separation	58% 2D, 69% 3D, 65% mix	Data – NSI and Expert interview	Expert interview (AVR)
7	% of additional residual waste mixed with plastic waste (from post-separation)	6%	Expert interview	Expert interview (AVR)
8	% of plastic type that is is recyclable	2D 89%; 3D 90%	Published paper – CE Delft	Plasticgebruik en verwerking van plastic afval in Nederland by CE Delft (2019)
9	% recovery rate of recyclable plastic (from KSI sorting facility)	2D 61%; 3D 90%	Published paper – MDPI and Expert input	Expert interview https://www.mdpi.com/2071-1050/12/23/10021/htm
10	% purity of plastic leaving KSI sorting facility and arriving at recycling plant	92% 3D; 94% 2D	Assumption – Meet DKR minimum standards	Duurzaam Door met de Kunststof Keten, Metropool Regio Eindhoven, 2015, Innoveren Denken Doe
11	% recovery rate in pellet creation (recycling plant)	Source-separation: 37-80% (mixed to PE) Post-separation: 33-82% (mixed to PE)	Published paper – WUR	Verbeteropties voor de recycling van kunststofverpakkingen"; E.U. Thoden van Velzen, M.T. Brouwer en C. Picuno, Food and Biobased Research. 2018

Costs

#	Metric	Value	Source type	Detailed source
12	Cost of regular residual waste collection	91€/t	Published paper – Vang-HHA	VANG Benchmark Household Waste – https://businessmonitor.azurewebsites.net/nvrd/Analyserapport_peiljaar_2020.PDF
13	Cost of separated plastic collection and handling – Urban areas (hoogbouwklasse A)	387€/t	Published paper – Vang-HHA	VANG Benchmark Household Waste – https://businessmonitor.azurewebsites.net/nvrd/Analyserapport_peiljaar_2020.PDF
14	Cost of separated plastic collection and handling – Urban areas (hoogbouwklasse D)	227€/t	Published paper – Vang-HHA	VANG Benchmark Household Waste – https://businessmonitor.azurewebsites.net/nvrd/Analyserapport_peiljaar_2020.PDF
15	% of households using mini-containers	92%	Data – Afvalmonitor	Afvalmonitor
16	Post-separator OPEX + CAPEX	40€/t waste = 212€/t of plastic (assuming a 12 year site economic lifetime)	Data – NSI + Assumption on return on capital	Informatieverzoek Strategy& inzake NSI; assumed return on capital of 8%
17	KSI OPEX + CAPEX	96€/t	Data + Assumption on return on capital	Site cost data + Equivalent Annual cost (EAC) at rate of return on capital of 8%
18	Recycler gate fee for plastic bales	PE, PET, PP (-150) €/t Foils and Mixed: 200 €/t	Expert interview	Expert interviews
19	Recycled plastic pellet sales prices	600-750 €/t (Foils to PE)	Expert interviews	Expert interviews
20	Recycling facility OPEX/ CAPEX	400 €/t	Assumption – Weighted combination of gate fees/costs and revenues from recycled pellet sales	Assumption: Weighted combination of gate fees/costs and revenues from recycled pellet sales
21	Cost of buying virgin plastic	632-830 €/t (Foils to PE)	Data – Plasticker	Plasticker
22	W2E OPEX/CAPEX	125 €/t	Data – SBE	Model: €110-140/t estimated bandwidth by PwC based on ECN, TNO, Vereniging Afvalbedrijven [Referenced: https://ee.sbe.vu.nl/nl/Images/Gradus_R._ea_A_CostEffectiveness_Analysis_For_Incineration_Or_Recycling_Of_Dutch_Household_Plastic_waste_tcm265-863321.pdf]

#	Metric	Value	Source type	Detailed source
23	Electricity MWh price	40 €/MWh	Published paper – Tennet	https://www.tennet.eu/fileadmin/user_upload/Company/Publications/Technical_Publications/TenneT_Annual_Market_Update_2019.pdf
24	Electricity generation efficiency	11%	Published paper – Energies	Eriksson, Finnveden (2017). Energies 10, 539. https://www.mdpi.com/1996-1073/10/4/539 Figure based on average efficiencies of CHPs in Table 2
25	Heat GJ price	6 €/GJ	Published paper – SBE	Bandbreedte 5-8; 5,9 volgens Regeling vaststelling correcties voorschotverlening duurzame energieproductie 2014 [https://ee.sbe.vu.nl/nl/Images/Gradus_R._ea_A_CostEffectiveness_Analysis_For_Incineration_Or_Recycling_Of_Dutch_Household_Plastic_waste_tcm265-863321.pdf]
26	Heat generation efficiency	62%	Published paper – Energies	Eriksson, Finnveden (2017). Energies 10, 539. https://www.mdpi.com/1996-1073/10/4/539 Figure based on average efficiencies of CHPs in Table 2
27	Energy content of plastic	26.4 GJ/t	Published paper – ICM	http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.baztech-7e80bdd8-9731-4ee5-b801-d5ce0d67395a/c/5_13__Siudyga_GB.PDF [Alternative source with c.40GJ/t https://www.tandfonline.com/doi/pdf/10.1080/10473289.1997.10464461]
28	Landfill gate fee (excl. tax, incl. returns)	25 €/t	Published paper – EEA	https://www.eea.europa.eu/data-and-maps/figures/typical-charge-gate-fee-and
29	Transport costs	0.04 €/kmt	Published paper	PwC analyse obv TNO 2012 [Referenced: https://ee.sbe.vu.nl/nl/Images/Gradus_R._ea_A_CostEffectiveness_Analysis_For_Incineration_Or_Recycling_Of_Dutch_Household_Plastic_waste_tcm265-863321.pdf]

CO_2

#	Metric	Value	Source type	Detailed source
30	Post separator operations CO_2	6 kg CO_2/t	Data – NSI + other data	Informatieverzoek Strategy& inzake NSI
31	KSI operations CO_2	70 kg CO_2/t	Expert interviews	Expert interviews
32	Recycling plant opertions CO_2	100 kg CO_2/t	Assumption – Multiple of KSI plant operatons CO_2	Assumption – Multiple of KSI plant operatons CO_2 given additional sorting, cleaning, melting required
33	Virgin pellet production emissions	1,694 kg CO_2/t	Data – ONS and Statista and Calculation	Calculated combining total plastic production and related emissions. UK ONS; Statista: https://www.statista.com/statistics/485966/co2-emissions-from-the-manufacture-of-plastic-products-uk
34	W2E operations CO_2	10 kg CO_2/t	Published paper – Europa	https://ec.europa.eu/environment/waste/studies/packaging/costsbenefitsannexes1_7.pdf
35	CO_2 emissions per ton plastic burnt	2,894 kg CO_2/t	Published paper – Ciel	https://www.ciel.org/wp-content/uploads/2019/05/Plastic-and-Climate-FINAL-2019.pdf
36	CO_2 emissions of alternative electricity production	2020: 275 kg CO_2/MWh 2030: 86 kg CO_2/MWh % Renewables: 8.4% (2019), 32% (2030)	Data – Europa; iea	https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-6#tab-googlechartid_googlechartid_googlechartid_googlechartid_chart_11111 https://www.iea.org/countries/the-netherlands https://www.government.nl/topics/climate-change/eu-policy
37	CO_2 emissions of alternative heat production	36 kg CO_2/t	Published paper – Utrechts	http://www.utrecht.nl/fileadmin/uploads/documenten/3.ruimtelijk-ontwikkeling/Milieu/CO2/Beschrijving_monitoring_bepaling_CO2_uitstoot_v4_32.pdf
38	Landfill operations CO_2	5 kg CO_2/t	Published paper – Europa	https://ec.europa.eu/environment/waste/studies/packaging/costsbenefitsannexes1_7.pdf
39	Transport CO_2 per km per ton	0,079 kg CO_2/t	Published paper – SBE	Visser&Smit 2010; voor meerdere typen afval [https://ee.sbe.vu.nl/nl/Images/Gradus_R._ea_A_CostEffectiveness_Analysis_For_Incineration_Or_Recycling_Of_Dutch_Household_Plastic_waste_tcm265-863321.pdf]

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