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A Cost-effectiveness Analysis for Incineration or Recycling of Dutch Household Plastic Waste☆

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ABSTRACT

The cost-effectiveness of two different plastic waste treatment options is compared. This paper evaluates the recycling of plastic waste with the more conventional incineration of plastic waste, using data for the Netherlands. Both options have specific revenues and costs. The main benefit from plastic recycling is the avoidance of CO_2 emissions that otherwise would occur during incineration and from the production of virgin (new) plastic material. At the same time, there are significant costs involved, such as collection, separation, sorting, and recycling. The benefit from plastic waste incineration is the energy that can be recovered, which reduces emissions in the regular energy production sector by displacing production. The main cost associated with incineration is that this requires a waste-to-energy plant with the associated capital investments. Summing the costs and revenues from both plastic waste treatment options and comparing the results, leads to an implicit CO_2 abatement price of 178 €/t of CO_2 in case of plastic recycling. In general, this implicit price is much higher than current (or historic) ETS prices, the estimated external costs of CO_2 emissions, or alternatives to reduce CO_2 emissions (e.g. renewable energy). A sensitivity analysis shows that this conclusion is robust.

1. Introduction

Lack of space and growing public environmental awareness forced subsequent Dutch governments to take measures from the early eighties to reduce the landfilling of household waste and to stimulate incineration and recycling (see Dijkgraaf, 2004). The percentage of Dutch municipal waste that was either recycled or composed in 2014 was 24% and 27% respectively. The remaining half was incinerated to recover energy (electricity and heat). The Dutch incineration facilities are amongst the most efficient in the world, with high energy recovery and competitive gate fees. Although there was some discussion at the beginning of this century whether the waste incineration should be considered from a cost-benefit perspective (see Dijkgraaf and Vollebergh, 2004), the Dutch government remains committed to its strict policy to stimulate waste recycling and incineration. In other countries, e.g. Germany and the USA, waste incineration has not been undisputed (for USA see for example Seltenrich, 2013). In the Netherlands some environmental groups even advocate a zero-waste policy (i.e. full recycling/re-use) without any form of incineration. The advocates of more recycling point to Germany, which has less waste incineration and a recycling rate (without composting) of 48% - two times the Dutch rate.

In the past decade, Dutch efforts to stimulate the collection of recyclable waste, especially at the source, have been intensified. Similar to most EU countries, Dutch municipalities are in charge of collecting and sorting household waste. Municipalities are thus, from an execution perspective, responsible for implementing national and European waste policies. Dijkgraaf and Gradus (2016a) show that between 1998 and 2012 there was an increase in municipally-run facilities to collect different valuable waste streams such as paper, glass and textiles. In addition, many municipalities introduced curbside collection of specific waste streams, and unit-based pricing for mixed waste to encourage recycling. In Ferreira et al. (2016) the costs (including opportunity costs) and revenues of different waste collection and sorting systems in Portugal, Italy (in particular, the Lombardia region), and Belgium are compared. The three countries differ in their collection systems. Some countries put emphasis on a drop-off system using centrally-located containers, whilst others focus on curbside systems (door-to-door source collection) and collection frequency. They further differ whether packaging material is collected as a mono-material stream (e.g. solely plastics) or as a multi-material stream. The authors conclude, for all three countries analysed, that re-routing packaging waste for recycling is better for the environment than other waste treatment

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options, such as incineration and landfilling. Given recent Dutch policy initiatives that specifically focus on plastic packaging waste, this article has a more specific focus.

Dutch recycling of plastic waste has drawn significant political and public attention. Since 2009 most Dutch municipalities separately collect plastic packaging at the source, and are financially compensated by the packaging industry – similar to other European countries (see da Cruz et al., 2014). Dutch municipalities are free in the plastic waste collection methodology. Both curbside door-to-door collection and central drop-off facilities are common, although the number of municipalities collecting household plastic waste at the curbside has substantially increased in recent years.

As a result, more Dutch plastic waste is recycled, contributing to a reduction in CO_2 emissions – as less plastic waste is incinerated and less virgin material is needed. However, the costs for the collection, separation, sorting and recycling of household plastic waste (funded by the packaging industry) substantially outweigh the revenues that are generated from the sale of recycled plastic. Therefore, municipalities are compensated for this deficit by the packaging industry and get a net contribution of 677 €/t of collected household plastic waste. In other words, the total cost of recycling of plastic waste is 677 €/t. In addition, recycling costs depend on the quality of the final secondary plastic material delivered. Producing plastics for high quality industrial purposes will require further separation and processing to meet required standards.

On the other hand, the incineration of plastic waste generates revenues from an energy perspective. Plastic waste produces more than three times more energy when compared to other materials (see also Morris, 1996). A decrease in the plastic content of municipal waste lowers the energy output per unit of input, and thus increases overall incineration costs (by reducing effectiveness and energy return). The difference in costs and benefits between the two different waste treatment options for plastic packaging in the Netherlands provide for an interesting analysis of relative costs and benefits from an economic and environmental perspective.

Hopewell et al. (2009) show that incineration of plastic waste is less prevalent than the recycling of plastics at household level. They also point out that for highly mixed plastics energy-recovery may be the most suitable option. As far as we know a cost-effectiveness analysis comparing household plastic recycling, with plastic waste collected separately at source (i.e. curbside), to the recovery of energy through plastic waste incineration has not been performed. This paper attempts to fill that gap. Both options – plastic recycling and energy recovery from plastic – have specific revenues and costs.

The benefit of recycling is the avoided CO_2 that would otherwise be released during incineration and during the production of virgin plastics (as plastic is based on hydrocarbons). At the same time, there are significant costs involved with collection, separation, and sorting of plastic packaging waste by municipalities and the production of new (recycled) plastic raw materials. The revenues of incineration are energy recovery such as heat and electricity production. The associated costs relate to the capital and maintenance expenditure of a waste-to-energy facility. To determine the cost effectiveness of plastic recycling the revenues, costs and environmental impact - expressed in CO_2 emissions - are compared to the alternative, energy recovery from plastic incineration. The implicit cost of the CO_2 avoidance is calculated by comparing the difference in the net costs with the difference in net CO_2 emissions. This (implicit) price can then be compared with other options to achieve equivalent CO_2 reductions. We show that our derived implicit price is higher than both current and historic ETS prices, external costs, and other alternatives, such as renewable power production. We include a sensitivity analysis to test the robustness of our conclusions and we demonstrate that, in general, this implicit price is indeed relatively high in comparison.

The remainder of this paper is organized as follows. Section 2 describes the producer responsibility for plastic packaging in the Netherlands. Section 3 presents the cost effectiveness analysis, where we first present the chosen methodology and the data, followed by the analysis itself. Section 4 presents the sensitivity analysis, and finally Section 5 concludes, discusses policy implications, and makes suggestions for further research.

2. Dutch Extended Producer Responsibility

Based on the European directive on packaging and packaging waste, packaging producers are responsible to separate and recycle plastic packaging waste. In the Netherlands a so-called "green dot" company is in charge of meeting these legal obligations (Stichting Afvalfonds Verpakkingen, referred to as the *Afvalfonds*). It collects a financial contribution paid by the retail sector and the packaging industry (based on volumes of plastic waste) and compensates municipalities, which – in the Dutch system – have been mandated by the *Afvalfonds* to collect household plastic waste. Therefore, the *Afvalfonds* provides a clear structure to meet legislative requirements. In most European countries it is organized in this way (see Marques and da Cruz, 2015).

The Netherlands has implemented this European legislation strictly. In 2014, 50% of (packaging) plastics was recycled and in 2022 the goal is 52%, which is almost double when compared to current EU legislation and more in line with EU plans for 2030.[1] As the target has already been met, some environmental groups, such as *Natuur&Milieu*, are arguing to set the 52% target for 2017 instead of 2022 (see KiDV, 2016).

In order to comply with the ambitious recycling targets, the *Afvalfonds* was granted a license to manage the flow of household plastics. Its task is to promote, coordinate and finance the collection, separation, sorting and recycling of municipal (packaging) plastic. The (packaging) industry in the Netherlands is coordinated through this *Afvalfonds* and pays a fee to the fund according to the level of plastic production. Most companies pay a fixed contribution for products that require plastic packaging, such as body care, cleaning etc. In the Netherlands, municipalities are responsible for the collection and treatment of municipal waste. In return for collecting plastic packaging waste for the producers, the *Afvalfonds* compensates the associated costs. In 2015, there were 393 municipalities in the Netherlands, which received a financial contribution from the *Afvalfonds*.[2]

Based on 2010 data by Marques and da Cruz (2015), the green dot fees differ widely between countries. For Belgium and France this was respectively 220 and 245 €/t plastic, for Germany it was circa 1430 €/t (based on 2007 data).[3] Marques and da Cruz (2015) discuss that these differences are driven in part by the scope of recycling policies, and thus which plastics are recycled. In Germany, for example, mixed plastics are recycled, whereas in Belgium only plastic bottles and flasks, metallic packaging, and drink cartons are separated. In the case of Belgium only plastic of higher quality is separated, which increases the subsequent revenues from the sale of secondary plastic, and thus leads to lower tariffs. This suggests that if recent European plans become legislation, green dot fees in countries like Belgium will need to be raised, making our cost-effectiveness analysis of the Dutch market relevant for other European countries.

As mentioned, Dutch municipalities are responsible for the collection of plastic packaging waste, but are allowed to decide how they organize this. Dijkgraaf and Gradus (2016a) show that in 2007–2012 37% of municipalities collected plastic packaging waste at the curbside, whilst in the remaining municipalities citizens have to drop-off plastic waste at collection points nearby schools and shopping centres. Over half of the curbside municipalities (59%) collected plastic waste once a

[1] According to a recent proposal (20/04/2016), the Commission proposes a national target of 55% by 2030.

[2] Also other packaging material such as glass, paper and metal receive a contribution from the *Afvalfonds*, but the contribution for plastics is the most important.

[3] This is based on Table 3.3 for Belgium, Table 3.5 for France and Table 3.12 for Germany and taking into account that 1 t is 0.907 (metric) tonne. It should noticed that this fee is not mandatory for Germany as it is a private arrangement between industry and several green dot companies and is based on the last publicly-available list. For other countries discussed in this book, their system is less comparable.

month and a quarter (27%) twice a month. Interestingly, the number of municipalities with door-to-door curbside collection increased from 37% in 2007–2012 to 63% in 2013–2014 (Dijkgraaf and Gradus, 2016b). At the same time the frequency has also increased on average in Dutch municipalities (see also Dijkgraaf and Gradus, 2016b) from 27% twice a month in 2007–12 to 48% in 2013–14.[4] In some municipalities - especially large cities such as Amsterdam - plastic waste collection is low or negligible. In the case of Amsterdam, an exemption was granted by the Dutch Ministry of Infrastructure and Environmental Affairs (*Ministerie van Infrastructuur en Milieu*). In 2012, 49 municipalities (12%) did not collect any plastic waste separately, although this exemption is limited in time. In addition, in some municipalities, especially in the north of the Netherlands, plastic waste is separated industrially after mixed municipal solid waste is collected at the curbside. However, this post-separation is (formally) not stimulated by central government and even not registered in the official accounts. In Section 5 we will discuss this issue of post-separation.

In the Netherlands all costs for collection, separation, sorting, and recycling packaging waste are fully reimbursed by the (packaging) industry. Each producer has to declare the volume of packaging waste it produces, whereas some products, such as body care or cleaning products, have a fixed-fee scheme. To avoid administrative costs, small supermarkets and packaging companies have been exempted. In 2015, approximately 2500 Dutch companies paid such a fee. These producers pay a fixed contribution per product, which is normally passed on to consumers.[5] In 2015 Dutch municipalities received a financial contribution of 677 €/t for separated plastic. This is more than the compensation in Belgium and France, but less than Germany.[6] In 2015, the costs for the *Afvalfonds* were almost 200 million Euros – equivalent to approximately 25 Euro per household. These costs include other packaging materials, such as glass, but also costs to minimise and avoid littering. However, the plastic tariffs are the most significant part of the total *Afvalfonds* costs, with 120 million Euros.

3. Cost-effectiveness Analysis

3.1. Method and Data

Dutch waste-to-energy plants employ state-of-the-art technology, which filters out most air pollutants as SO_2 and NO_x. This is the result of additional national environmental standards, in excess of minimum European requirements. The Swedish incineration of plastic emits fewer pollutants, such as SO_2 and NO_x, when compared to the incineration of mixed municipal solid waste (Eriksson et al., 2005). Furthermore, Dijkgraaf and Vollebergh (2004) show in their comparison of Dutch incineration versus landfilling that -based on the technology in the nineties- for the emissions to air CO_2 dominates environmental costs as environmental costs resulting from CO_2 emissions accounts for 90% of total environmental costs. Therefore, in this article we focus on CO_2 emissions and ignore the effects of SO_2 and NO_x, given their limited impact. By comparing the costs and revenues of both plastic treatment options from a CO_2 perspective, we derive the implicit price for avoiding the emission of one tonne CO_2, which can then be compared with other options to reduce emissions.

To assess the relative cost effectiveness of plastic recycling, the specific revenues and costs of both options are compared.[7] In Table 1 the main publicly-available data and sources are specified. In the next section we explore this information in a cost-effectiveness analysis.

There is no publicly-available information regarding the costs of collection, separation, sorting, and recycling of plastic waste in the Netherlands. We therefore use the remuneration fees that are provided to municipalities by the *Afvalfonds* as a proxy for the actual costs. These fees are based on negotiations between the *Afvalfonds* and the Association of Dutch municipalities (VNG). Fees for 2015 were published in 2014. Further, the remuneration is a fixed fee per tonne plastic waste and is equal for all municipalities. This implies that some municipalities may be compensated in excess of actual costs and vice versa. Although the costs and revenues are evaluated on a regular basis, there are some indications that this bargaining between municipalities and the *Afvalfonds* does not provide a strong incentive for cost reduction and innovation. We view the remuneration fee as the best available proxy of actual costs. As this approach is a best guess of the costs, we test the sensitivity of the results to changes in the fees (see Section 4).

Table 1
Core information of the analysis.

Input	Figure	Source
Plastic characteristics		
Plastic heating value	29 MJ/kg	Bergsma et al. (2011): range of 23–42 MJ/kg
Waste incineration parameters		
Electricity generation efficiency	21%	Based on Rijkswaterstaat (2013)
Heat production efficiency	20%	Based on Rijkswaterstaat (2013)
Collection costs mixed waste	56 €/t	NVRD (2014)
Incineration costs mixed waste	125 €/t	Integral cost price based on Waste and Resources Action Programme (WARP) average UK gate fee in 2015[a]
CO_2 emissions plastic waste incineration	2599 kg/t	Average of 2188 kg/t and 3010 kg/t; based on Benner et al. (2007)
Recycling parameters		
Plastic recovery percentage	75%	Dutch Association of Municipalities (2014b)
Collection remuneration 2015	408 €/t	Dutch Association of Municipalities (2014a)
Post-collection 2015	204 €/t	Dutch Association of Municipalities (2014a)
Net market costs 2015	65 €/t	Dutch Association of Municipalities (2014b)
CO_2 emission due to energy consumption recycling		271 kg CO_2/t
Average of 283 kg/t and 259 kg/t based on Benner et al. (2007)		
Transport parameters		
Distance to waste incineration	100 km	Assumption: 50 km twice
Distance to sorting installation	100 km	Assumption: 50 km twice
Distance to granulate producer	200 km	Assumption: granulate producer based in Germany
CO_2 emission of road transport		0.08 kg/km t
Visser and Smit Bouw (2010)		
Costs of road transport	0.04 €/km t	Based on Groen et al. (2012)
Price parameters		
Electricity price	50 €/MWh	Based on average cal. 2015 APX prices
Heat and steam price	6 €/GJ	Ministry of Economic Affairs (2013)

[a] See http://www.wrap.org.uk/content/latest-gate-fees-trends-revealed-wrap. We take the average of 65 and 132 GBP and convert to Euros using an exchange rate of 1.27. This is also in line with private WTE production costs for US, Germany and Sweden as found in Miranda and Hale (1997, Table 9).

[4] Twice a month was interpreted as 24, 25 and 26 times a year. In a very limited number of municipalities (i.e. 6) plastic waste was collected every week.

[5] Marques and da Cruz (2015, Table 3.2) show that this fixed contribution for Belgium can range from € 0.17 for TV to € 0.0006 for tobacco.

[6] To make comparable figures between countries, inflation between 2007/2010 and 2015 should be included. Therefore, based on Marques and da Cruz (2015) Germany green dot fees are 1530 €/t and this is for Belgium and France respectively 227 and 253 €/t plastic.

[7] This is similar to Table 2 in Ferreira et al., 2016. It should be noted that in the Netherlands there are no subsidies from the government for waste collection.

We assume that one tonne of mixed plastic waste, which is collected, separated, sorted and transported to a recycling company, is based on the mass balance of separated plastic waste from households. Generally speaking, this source is more polluted than separated plastics from businesses. The recycling rate for this collected mixed plastic is 75%, meaning that 25% of the collected household plastic is still used for energy recovery (Dutch Association of Municipalities, 2014b). With the removal of plastic waste from mixed municipal waste, a loss of heat and electricity is created that would otherwise be recovered and produced by the waste-to-energy plant. We assume that the energy content of the displaced plastic is purchased at market prices – adjusted for conversion losses. The revenues for electricity and heat are estimated based on available market data.[8] The conversion efficiencies are based on the average efficiencies of Dutch waste-to-energy plants as indicated by Rijkswaterstaat (2013).[9]

We assume that if plastic waste is incinerated, it is not collected separately and is transported using the regular collection infrastructure. Therefore, there is a deficit in the amount of recycled plastic that is available. These are presented as opportunity costs of incineration. To ensure comparability with recycling, the calculations are based on one tonne of mixed plastic, but now produced from virgin material.

If plastic waste is recycled, less energy is produced by waste-to-energy plants. This deficit is similar to the secondary plastic deficit. To make it comparable with incineration, the calculations are based on the same energy output, but now produced through regular electricity generation. These are presented as the opportunity costs of recycling. The full cost (including both operational and capital expenditure) of the waste-to-energy plant is based on publicly-available information. The costs for bottom ash are included in the analysis, although in case of plastic waste incineration these costs are relatively small.

3.2. The Cost-effectiveness Analysis

In Table 2 costs and revenues are given for plastic waste recycling and energy recovery from plastic.

First, private costs of collection and treatment are taking into account. For plastic waste incineration, the transport costs are 4 €/t and the collection costs are 56 €/t, which sum up to 60 €/t. For plastic waste recycling, the collection and transport costs are 408 €/t. A detailed split is not possible, given the fact that the *Afvalfonds* remuneration is an all-in fee that bundles all the individual cost components. It should be noted however, that collection and transportation costs of separated plastic waste are substantially higher than for normal waste. This is due to the fact that the density of plastic waste is considerably lower than mixed municipal waste. In other words, more transport is needed per tonne for plastic than for more dense waste streams. Furthermore, in most municipalities a separate infrastructure of collection points and curbside collection of plastic waste is needed (Dijkgraaf and Gradus, 2016a,b). This infrastructure requires a substantial upfront investment and regular extra collection costs for trucks and workers. Since the volume of separately collected plastic waste is low, this results in high costs per unit of collected plastic waste.

Second, net treatment costs are derived by subtracting the revenues generated by the sale of secondary plastic from the total plastic waste treatment cost. The net treatment cost of plastic waste recycling is substantially higher than for plastic waste incineration. We take into account the revenues from the sale of secondary plastic in case of plastic waste recycling, and energy in case of plastic waste incineration. The net treatment costs are 269 €/t of plastic for the recycling option, whilst the net treatment costs are 6 €/t for the incineration option. The net costs of plastic recycling are based on post collection of € 204 and costs (and revenues) of selling and transporting secondary plastics of € 65. The net costs of energy recovery are based on incineration costs of € 125 and revenues from generated electricity of € 85 and revenues from generated heat of € 35. In summary, total (monetary) costs are 677 €/t of plastic for the plastic waste recycling option, whilst the costs for energy recovery from plastic waste are 66 €/t.

Table 2
Net costs of recycling and incineration plastic waste in €/t.

	Recycling	Incineration
Collection and transport costs	408	60
Net-treatment costs	269	6
Sub-total	677	66
Opportunity costs energy	90	
Opportunity costs plastics		495
Total	767	561

Third, we take into account the opportunity costs of plastic waste recycling in case of plastic incineration, and vice versa the opportunity costs of energy recovery from plastic waste in case of plastic waste recycling (see also Ferreira et al., 2016). In other words, in case plastic waste is source-separated and recycled, and hence no longer incinerated, there is an energy deficit, which needs to be compensated. Alternatively, in case plastic waste is not source-separated and recycled but incinerated, there is a secondary plastic deficit, which needs to be taken into account. The energy deficit in case of plastic waste recycling is equal to 90 €/t – the equivalent energy value of the recycled plastic waste that would otherwise have been used for energy recovery.[10] In the case of plastic waste incineration a shortfall in the volume of secondary plastic (recycled plastic waste) is created. The value of recycled plastic waste that is lost due to incineration is 495 €/t.[11]

In summary, the net costs of one tonne of plastic waste recycling are considerable higher than for energy recovery from plastic waste.[12] The total costs for recycling plastic waste are 767 €/t and for energy recovery from plastic waste 561 €/t, resulting in a difference of 206 €/t.

In Table 3 CO_2 emissions of both options are presented.

Based on the current Dutch incineration technology one tonne plastic waste yields 2.6 t of CO_2 (Benner et al., 2007).[13] As 25% of the recycled plastic waste is finally incinerated, separating one tonne plastic waste yields 0.65 t CO_2 through energy recovery. Plastic waste recycling is an advanced industrial process that emits CO_2 as well, mostly due to the energy consumed. Based on Benner et al. (2007), we assume that recycling 0.75 t of plastic waste yields 0.2 t CO_2. In addition, the transport of plastic waste causes some CO_2 emissions, although this is relatively limited.

Similar to the missed revenues or costs from choosing between the alternative plastic waste treatment options, we also estimate the missed emissions between the two options. The opportunity emissions are based on the most common alternative production process for producing either energy or secondary plastic granulate. For electricity, this is based on the average generation mix in the Netherlands, including renewable and conventional production. For the generation of heat the most common alternative process is the use of gas turbines. We assume that the opportunity emissions for secondary plastic granulate are the

[8] For heat and steam price we take the publicly-available information in February 2015. There are indications that currently this is somewhat higher, decreasing the cost-effectiveness in Section 3.2.

[9] For the Netherlands, the energy content of plastics is between 22.95 and 42.47 MJ for 1 kg plastic (Bergsma et al., 2011). We assume a conservative 29 MJ/kg for plastic in the analysis. The energy content of 1 kg mixed household waste is about 9 MJ (Rijkswaterstaat, 2013).

[10] We take 75% of this, as we assume in the plastic waste recycling case that 25% of the separated plastic waste will be incinerated.

[11] The base price of 495 €/t is based on the average 2014 prices extracted from www.plasticker.de, accessed on February 2015 and weighed by the household plastic volume mix. As 2014-inflation (i.e. 0.1%) was almost zero we use the same price.

[12] Taking into account that on average Dutch households separate circa 15 kg, the net costs of plastic waste recycling are 12 Euro per annum.

[13] In a recent study in May 2016 there are some indications that for recent plants the incineration process has become more efficient and has resulted in lower CO_2 emissions, leading to a worsening of the cost effectiveness (see Bijleveld et al., 2016). However, as we do not have this information for all plants we take the 2007-figures in the calculations.

Table 3
CO_2 emissions of recycling and incineration in tonne CO_2 per tonne plastic waste.

	Recycling	Incineration
Energy recovery	0.65	2.60
Recycling	0.20	
Transport	0.02	0.01
Sub-total	0.87	2.61
Opportunity emissions energy	0.78	
Opportunity emissions plastics		0.20
Total	1.66	2.82

Source: own calculations based on Table 1.

typically-associated emissions of I industrial-scale plastic recycling, as no other process can generate this quality of plastic granulate.

From Table 3 it follows that the CO_2 emissions from the energy recovery option are 1.16 t higher than for the recycling option. This difference is mainly driven by higher CO_2 emissions from the incineration of plastic waste. By using the difference in costs and the difference in CO_2 emissions between both options, the cost-effectiveness of plastic waste recycling can be calculated and expressed in an implicit CO_2 price. Based on our analysis we find that the shadow price of one tonne of CO_2 reduction by means of plastic waste recycling is equal to 178 € (206 €/1.16 t of CO_2).

To place this implicit CO_2 price into perspective we compare it with other prices and viable alternatives. During early 2016, the market price for CO_2 emissions in the European Emissions Trading scheme (ETS) was approximately 6 €/t.[14] This low price can be explained by the surplus of rights after the second trading period and the European crisis (Bel and Joseph, 2015). It is clear that our shadow price is much higher than the current (or historic) ETS price. That is to say, the current market price for a reduction of 1 t of CO_2 is 30 times lower than the implied price when recycling plastic waste instead of recovering energy from incineration. If we take 50 €/t CO_2 as an average value for the social cost of carbon emissions, this is still substantially lower than the shadow CO_2 price for recycling plastic waste.[15] As Tol (2008) shows, this estimate depends on the discount rate and the weight of equity (between countries). In this meta-study, he also points that the distribution of the social cost of carbon[16] is a fat right tail distribution, suggesting that there is a chance that total social costs are even larger than the price of one tonne of CO_2 reduction by means of plastic waste recycling. Therefore, from a policy perspective, it is important to compare it with real alternatives, such as wind energy, solar PV energy, or CO_2 capture and sequestration (CCS). Based on recent long-term calculations it was demonstrated that the costs of reducing one tonne CO_2 is 29 € for wind energy and 81 € for solar PV.[17] One of the more expensive options in the energy sector – CCS in the North Sea – costs between 80 and 90 €/t of CO_2 (te Roller, 2011). The cost of this option is still substantially lower than our shadow price plastic waste recycling. In other words, the CO_2 emission reduction achieved by plastic recycling is expensive when compared to conventional and market CO_2 prices, and the alternative technologies available.

4. The Sensitivity Analysis

To examine the robustness of our main conclusions we undertake a sensitivity analysis under a set of reasonable alternative assumptions. The sensitivity of the cost effectiveness is assessed using three scenarios. The results are presented in Table 4, after the presentation of the base scenario.

In Section 3, we assume that the opportunity emissions as a result of recycling plastic waste was based on the average energy mix in the Netherlands. In the first sensitivity we assume that the replacement energy is renewable energy with no CO_2 emissions (i.e. fully CO_2 neutral). This decreases the corresponding CO_2 emissions from 0.78 per tonne to 0 per tonne in Table 3. In this case, the difference in CO_2 emissions will be lower in favour of energy recovery and thus the emission gap increases, but the costs stay the same (see Table 4).

In the scenario where renewable energy is used to replace the displace energy due to recycling of plastic waste instead of incineration, the cost effectiveness of decreases from 178 to 106 €/t of CO_2 (206 €/1.94 t of CO_2). Although the decrease is substantial, the implicit CO_2 price remains higher than other viable alternatives.

In the second sensitivity we examine the effect of higher secondary plastic prices.[18] Improving the market for secondary plastic (for example, by using more attractive applications or incentivising producers to source a certain percentage of recycled material) or improving the quality of the output (through targeted innovations in the recycling production process), can increase the yield of secondary plastic and thereby improve the cost effectiveness. In the second sensitivity we assume that the price of secondary plastic will rise by 10%, from 495 to 544 €/t.[19] The cost effectiveness, as a result, decreases to 92 €/t (see Table 4). As with the first sensitivity, the effect of a price increase in the output from plastic waste recycling has a positive effect on the cost effectiveness. However, the implicit price per tonne of CO_2 remains relatively high.

In the third sensitivity we alter the assumptions regarding collection costs, as these costs dominate the costs for plastic waste recycling. Two-thirds of the total *Afvalfonds* remuneration fee is related to collection and transportation costs. One of the problems with the collection of household plastic waste is the relatively small volumes – approximately 15 kg per household per year in the Netherlands. As Dijkgraaf and Gradus (2015) show, there are several ways to reduce collection and transportation costs. First, Dutch municipalities[20] could introduce unit-based pricing of mixed and compostable waste as a measure to stimulate the separate collection of recyclables. It is well-known that unit-based pricing systems are effective in stimulating recyclable waste, such as plastics (see Allers and Hoeben, 2010). Second, non-monetary initiatives, such as the provision of frequent curbside recycling services and reducing the collection frequency of residual waste could encourage recycling as well. For US municipal data, Beatty et al. (2007) find a statistically significant relation between the percentage of population served by curbside programs and the amount of recycled plastics. However, based on Dutch municipal data, Dijkgraaf and Gradus (2016a) do not find a (statistically significant) relationship between the collection frequency of plastic waste and the quantity collected. The authors find that a separate bag or bin significantly increases the volume of collected plastic.[21] Third, there is some evidence that the privatization of refuse collection can be an attractive alternative (see Dijkgraaf and Gradus, 2003). However, later research for the

[14] For an overview of prices see http://www.investing.com/commodities/carbon-emissions (accessed on February 28, 2016).

[15] This is based on EEA (2008), which uses a low value of 19 Euro and a high value of 80 Euro. Note, however, that EU (2014) uses a price of only 33 €/t of CO_2 for the social cost.

[16] Tol (2008) makes use of a Kernel-distribution.

[17] Assuming a long term electricity price of 0.05 Euro per kWh, the current subsidy in the Netherlands for solar electricity is 0.073 Euro and for wind 0.026 Euro. Using the emission of CO_2 for old coal fired electricity plants, the plants that are substituted for green energy, of 900 g per kWh, the implied CO_2 price is respectively 81 and 29 €/t CO_2 (see also Greenpeace (2015).

[18] It should be noted that recycling plastic waste produces secondary plastic raw materials, which do not directly compete with primary (virgin) plastic. An analysis of the correlation between market prices of secondary plastic and oil prices, shows that the price of secondary plastic is only marginally dependent on the price of oil. The price for secondary plastic granulate is lower than the price for virgin material, as the use of secondary plastic granulate is limited due to lower quality. Secondary plastic granulate can therefore not be used as replacement for virgin material, without substantial costly quality improvements.

[19] If the price of plastic is decreasing with 10%, the cost effectiveness of incineration against recycling increases from 178 €/t to 264 €/t.

[20] One third of Dutch municipalities have a unit-based pricing system (see Dijkgraaf and Gradus, 2015).

[21] Also Abbott et al. (2011) found that bags for dry recyclables with a "non-reusable" sign increases the dry recycling rate.

Table 4
Costs of CO_2 reduction between plastic waste recycling and incineration per scenario.

	Cost gap (€)	CO_2 emission gap (t)	Costs of CO_2 reduction (€/t)
Base scenario	206	1.16	178
Scenario 1: CO_2 neutral replacement energy	206	1.94	106
Scenario 2: Plastic price increase +10%	107	1.16	92
Scenario 3: 2019 remuneration fee	86	1.16	74

Netherlands shows less cost saving potential due to market concentration risks (see Dijkgraaf and Gradus, 2007, and Gradus et al., 2016).

In 2019 the *Afvalfonds* remuneration fee is projected to be lowered from 677 to 557 €/t, as a result of lower collection costs.[22] However, the exact fee will be renegotiated in 2017 and this reduction serves as a lower bound – as agreed in the multi-year framework agreement. In this projection an expected change in the plastic price has been incorporated. In the third sensitivity, the (projected) remuneration fee in 2019 acts as the basis for the reduction in collection costs (a decrease from 677 €/t in 2015 to 557 €/t in 2019). The remuneration fee reduction increases the cost effectiveness from 178 to 74 €/t of CO_2. Of the three sensitivities this reduction has the largest impact on the cost effectiveness and brings the implicit price in the range of CCS solutions.

A combination of sensitivities leads to a significant increase in the cost effectiveness. When the lower collection costs (including new secondary plastic prices) are combined with the renewable energy replacement for displaced plastic waste incineration, the resulting implicit CO_2 price is 44 €/t. The implicit CO_2-price is then within the estimated external costs and could be considered cost effective.

5. Conclusions

The CO_2 reduction realised by Dutch plastic waste recycling is extremely expensive when compared to market-based and external cost CO_2 prices, and alternative viable technologies, such as wind, solar, and CCS. Based on a cost effectiveness analysis we show that the implicit price of reducing one tonne of CO_2 is 178 € under the current plastic waste recycling scheme, which is substantially more than the current ETS prices or the external costs. We show that there are two reasons for this. First, the collection and treatment costs of plastic waste are high. The collection costs for plastic waste are almost seven times the collection costs of mixed waste. In addition, the process and treatment costs of recycling are high, even if the (modest) revenues of recycled mixed plastics are taken into account. Second, the reduction in CO_2 emissions from plastic recycling is low. An average Dutch household separates approximately 15 kg of plastic waste and thereby saves 26 kg of CO_2 per annum. It would take an average household sixty years to compensate the CO_2 emissions of a single airplane trip (in economy class) from Amsterdam to Los Angeles.

Moreover, based on a sensitivity analysis we show that the conclusions still hold if the main assumptions are relaxed. If collection costs are substantially reduced with 120 €/t, the cost effectiveness improves from 178 to 74 €/t of CO_2 – still significantly higher than the external costs given in the literature. Although our analysis relies on Dutch data, the results are likely to be applicable for other countries given the increasing focus on plastic recycling by the European Commission.

This cost effectiveness analysis has several implications for policy and future research. One can argue that incineration, if done in an efficient way and with filtering out most air pollutants as SO_2 and NO_x, is not a bad alternative. If, however, one wants to avoid incineration – as European policy suggests – it is important that the cost of plastic recycling is reduced and innovation is stimulated. In order to increase innovation, and thus create opportunities for cost reduction, policies should focus on encouraging innovation in plastic recycling as opposed to focusing on the simplistic recycling goal for different materials. Thus, emphasis should be placed on stimulating and encouraging higher quality recycling, rather than simply more recycling. In addition, we suggest to analyse whether industrial-scale post-separation of plastic waste is an alternative. This technology allows for mechanical separation of waste, rather than requiring source-separation by householders. In the Netherlands as in many other European countries such policies are not stimulated by the central government. Nevertheless, post-separation can be very effective and reduce costs, by increasing plastic recovery levels and significantly reducing collection costs (see Dijkgraaf and Gradus, 2016b). Evidence from the north of the Netherlands shows that post-separation leads to larger volumes and higher quality of plastics, although there is limited public information on costs and thus on corresponding returns that are realised. However, as waste reduction and recycling behaviour are driven by different motivators (see D'Amoto et al., 2016), it is important to investigate the effect of promoting post-separation also in relation to unit-based pricing systems on plastic waste production by households as well.

[22] In 2019 it is expected that collection and post-collection remuneration will respectively become 299 and 193 €/t plastic waste.

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