Plastic Waste Handling and its Influence on Household Waste Incineration
A forward looking study for the County of Stockholm

Paolo Fornaseri

Master of Science Thesis
Stockholm 2012
Paolo Fornaseri

Plastic Waste Handling and its Influence on Household Waste Incineration
A forward looking study for the County of Stockholm

Supervisors:
Monika Olsson
Maria Malmström
Examiner:
Monika Olsson

Master of Science Thesis
STOCKHOLM 2012

PRESENTED AT

INDUSTRIAL ECOLOGY
ROYAL INSTITUTE OF TECHNOLOGY
Abstract

This study, aiming to support the future decision-making, presents a model that tries to evaluate the effects of different combinations of likely future changes in the mixed waste generation and of conservative or innovative organisations of the plastic waste handling in the County of Stockholm in the year 2030. The criteria chosen for the evaluation are the energy generated (heat to be used in the district heating network and electricity) from the incineration of plastic waste (which represents nowadays the predominant treatment option for the plastic waste generated in the County of Stockholm) and the amount of virgin raw materials (fossil fuels) needed for the replacement of the plastics not successfully recycled. The results show the importance of the harmonization among the plastic waste composition, the waste collection system and the recycling processes in order to reach a more sustainable configuration of the system. However the uncertainty of some input data hinders a neat evaluation relatively to the selected scenarios.
Acknowledgements

I would like to thank my supervisor Monika Olsson, who has given me the possibility of developing the project almost independently and my examiner Maria Malmström, whose help was fundamental in structuring my thinking and my writing.

Other thanks are for the people from the companies (Fortum AB, Fiskeby AB, FTI AB, Hans Andersson AB and Il Recycling AB) and the institutions (City of Stockholm, Swedish Government) that have provided me support in this study, being available for interviews and supplying the requested data.

Finally, I would like to thank as well all my corridor mates, my Erasmus friends, my brother and my parents, who have endured and coped with my annoying and repetitive reasoning about this thesis project.
# Table of Contents

Abstract ................................................................................................................................................... I
Acknowledgements ................................................................................................................................ II
Table of Contents .................................................................................................................................. III
Symbols .................................................................................................................................................. V
Introduction ........................................................................................................................................... 1
Aims and Objectives ............................................................................................................................... 5
Methodology ........................................................................................................................................... 6
  Waste Input-Output Modelling .......................................................................................................... 6
  Gathering of data ............................................................................................................................... 7
Waste Management System Analysis ................................................................................................... 8
  Spatial Boundaries.............................................................................................................................. 9
  Temporal Boundaries......................................................................................................................... 9
  Stakeholders Involved ....................................................................................................................... 10
  Concerns and Priorities of the Stakeholders .................................................................................... 11
Possible future changes and scenarios selection ................................................................................ 16
  Scenario 1 – Current Plastic Waste Handling Setting with future waste generation ...................... 18
  Scenario 2 – Agreement among production and plastic recycling system ...................................... 18
  Scenario 3 – Current handling system with high sorting rates forced by the legislation ............... 19
  Scenario 4 – Collection organised by polymer without agreement with the production system ... 19
Numerical Derivations of Scenarios ................................................................................................. 19
Modelling ............................................................................................................................................. 24
  Structure of the Model..................................................................................................................... 24
  Assumptions, Simplifications and Exclusions ................................................................................ 31
  Aggregated Evaluations for Scenarios Comparison ....................................................................... 33
Model Testing....................................................................................................................................... 36
Modelling Results ................................................................................................................................. 43
  Sub-Model 1: Mixed Household Waste Incineration .................................................................... 43
  Sub-Model 2: Recycling of sorted plastic waste ............................................................................ 46
Aggregated Results ............................................................................................................................... 49
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$rec_i$</td>
<td>Sorting Rate, $i^{th}$ waste fraction</td>
<td>[%]</td>
</tr>
<tr>
<td>$var_i$</td>
<td>Variation in percentage of the waste generation in respect to the Base Case, $i^{th}$ waste fraction</td>
<td>[%]</td>
</tr>
<tr>
<td>$A_{AVG\ WtoE}$</td>
<td>Average ashes fraction of waste to incineration</td>
<td>[%]</td>
</tr>
<tr>
<td>$A_i$</td>
<td>Ashes fraction, $i^{th}$ waste fraction</td>
<td>[%]</td>
</tr>
<tr>
<td>$CF_{AVG\ WtoE}$</td>
<td>Average combustible fraction of waste to incineration</td>
<td>[%]</td>
</tr>
<tr>
<td>$CF_i$</td>
<td>Combustible fraction, $i^{th}$ waste fraction</td>
<td>[%]</td>
</tr>
<tr>
<td>$DC_i$</td>
<td>Dirtiness coefficients, amount of food waste contaminating the packaging over the total weight of the packaging measured during the picking analysis</td>
<td>[%]</td>
</tr>
<tr>
<td>$ECR_i$</td>
<td>Per-capita Energy Content of recycling residuals, $i^{th}$ waste fraction</td>
<td>[MJ/pers/year]</td>
</tr>
<tr>
<td>$EC_i$</td>
<td>Per-capita Energy Content, $i^{th}$ waste fraction</td>
<td>[MJ/pers/year]</td>
</tr>
<tr>
<td>$EL_{forREC_i}$</td>
<td>Per-capita yearly electricity use for plastic recycling, $i^{th}$ waste fraction</td>
<td>[MJ/pers/year]</td>
</tr>
<tr>
<td>$EL_{fromWX_i}$</td>
<td>Per-capita electricity generated yearly, sub-model X, $i^{th}$ waste fraction</td>
<td>[MJ/pers/year]</td>
</tr>
<tr>
<td>$FFP_{fromVRMX_i}$</td>
<td>Per-capita yearly fossil fuels for plastic production from virgin raw materials, sub-model X, $i^{th}$ waste fraction</td>
<td>[kg oil/pers/year]</td>
</tr>
<tr>
<td>$HV_{AVG\ WtoE}$</td>
<td>Average heating value of waste to incineration, wet base</td>
<td>[MJ/kg]</td>
</tr>
<tr>
<td>$HV_{AVG\ WtoEd}$</td>
<td>Average heating value of waste to incineration, dry base</td>
<td>[MJ/kg]</td>
</tr>
<tr>
<td>$HV_{Design\ INC.}$</td>
<td>Heating value for which the incinerators is designed</td>
<td>[MJ/kg]</td>
</tr>
<tr>
<td>$HV_i$</td>
<td>Heating value, $i^{th}$ waste fraction</td>
<td>[MJ/kg]</td>
</tr>
<tr>
<td>$H_{fromWX_i}$</td>
<td>Per-capita heat generated yearly, sub-model X, $i^{th}$ waste fraction</td>
<td>[MJ/pers/year]</td>
</tr>
<tr>
<td>$M_{AVG\ WtoE}$</td>
<td>Average moisture content of waste to incineration</td>
<td>[%]</td>
</tr>
<tr>
<td>$MLC_i$</td>
<td>Material loss coefficient in the recycling plant, $i^{th}$ waste fraction</td>
<td>[-]</td>
</tr>
<tr>
<td>$M_i$</td>
<td>Moisture content, $i^{th}$ waste fraction</td>
<td>[%]</td>
</tr>
<tr>
<td>$PP_{fromVRMX_i}$</td>
<td>Per-capita amount of plastic to be produced yearly from virgin raw materials, sub-model X, $i^{th}$ waste fraction</td>
<td>[kg/pers/year]</td>
</tr>
<tr>
<td>$PR_i$</td>
<td>Per-capita amount of plastic recycled yearly, $i^{th}$ waste fraction</td>
<td>[kg/pers/year]</td>
</tr>
<tr>
<td>$P_{notR\ forVPS_i}$</td>
<td>Per-capita amount of plastic recycled yearly but not</td>
<td>[kg/pers/year]</td>
</tr>
</tbody>
</table>

Symbols
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$RR_i$</td>
<td>Per-capita yearly recycling residuals, $i^{th}$ waste fraction</td>
<td>[kg/pers/year]</td>
</tr>
<tr>
<td>$VPSC_i$</td>
<td>Virgin Plastic Substitution Coefficient, $i^{th}$ waste fraction</td>
<td>[%]</td>
</tr>
<tr>
<td>$WGd_i$</td>
<td>Per-capita waste generated yearly, $i^{th}$ waste fraction, dry</td>
<td>[kg/pers/year]</td>
</tr>
<tr>
<td>$WG_i$</td>
<td>Per-capita waste generated yearly, $i^{th}$ waste fraction</td>
<td>[kg/pers/year]</td>
</tr>
<tr>
<td>$WS_i$</td>
<td>Per-capita waste sorted yearly, $i^{th}$ waste fraction, dry</td>
<td>[kg/pers/year]</td>
</tr>
<tr>
<td>$WtoEd_i$</td>
<td>Per-capita waste incinerated yearly, $i^{th}$ waste fraction, dry</td>
<td>[kg/pers/year]</td>
</tr>
<tr>
<td>$WtoE_i$</td>
<td>Per-capita waste incinerated yearly, $i^{th}$ waste fraction</td>
<td>[kg/pers/year]</td>
</tr>
<tr>
<td>$WtoEinPA%_i$</td>
<td>Percentage of waste in the picking analysis, $i^{th}$ waste fraction</td>
<td>[%]</td>
</tr>
<tr>
<td>$\eta_{heat,WtoE}$</td>
<td>Incinerator efficiency for heat production</td>
<td>[%]</td>
</tr>
<tr>
<td>$\eta_{heat,CHP}$</td>
<td>Combined Heat and Power fossil fuels plant efficiency for heat generation</td>
<td>[%]</td>
</tr>
<tr>
<td>$\eta_{el,WtoE}$</td>
<td>Incinerator efficiency for electricity production</td>
<td>[%]</td>
</tr>
<tr>
<td>$\eta_{el,CHP}$</td>
<td>Combined Heat and Power fossil fuels plant efficiency for electricity generation</td>
<td>[%]</td>
</tr>
<tr>
<td>$BC,X$</td>
<td>Value assumed by quantity X in the Base Case scenario</td>
<td>[variable]</td>
</tr>
<tr>
<td>$EA$</td>
<td>Per-capita yearly Electricity available from incineration (reduced by the needs for recycling)</td>
<td>[MJ/pers/year]</td>
</tr>
<tr>
<td>$EA_{,FFPP_{,Var}}$</td>
<td>Per-capita electricity available correction due to the constant fossil fuels use hypothesis, yearly</td>
<td>[MJ/pers/year]</td>
</tr>
<tr>
<td>$FFPP$</td>
<td>Overall amount of fossil fuels needed to replace plastic yearly</td>
<td>[kg oil/pers/year]</td>
</tr>
<tr>
<td>$HA$</td>
<td>Per-capita yearly Heat available from incineration</td>
<td>[MJ/pers/year]</td>
</tr>
<tr>
<td>$HA_{,FFPP_{,Var}}$</td>
<td>Per-capita heat available correction due to the constant fossil fuels use hypothesis, yearly</td>
<td>[MJ/pers/year]</td>
</tr>
<tr>
<td>$X_{,pmp}$</td>
<td>X quantity expressed per mass of plastic collected or processed</td>
<td>[variable]</td>
</tr>
</tbody>
</table>
Introduction

In the last decade, the willingness to reduce landfilling, driven by the European legislation (Directive 1999/31/EC) and translated in specific taxes against this practice in several countries (Lag (1999:673) om skatt på avfall), has stimulated the expansion of the incineration capacity throughout Europe and above all in Sweden (EEA 2009). Despite the low efficiency in the electricity production (Worrell & Vesilind 2012), the use of the waste heat in a district heating network is attractive in cold and densely populated areas. Not even the complexity of the end-of-pipe treatments needed to restrain the emissions, which result in high fixed costs (O. Nyström et al. 2011), represents a limit to the installation of new incinerators. In fact, considering the County of Stockholm, the amount of waste manageable in waste-to-energy plants is going almost to double in the next years (reaching a treatment capacity above 1200000 tons of waste per year), with the activation of a new burner in Brista and with the upgrade of the boilers in Högdalen (Lindman 2012).

The design of these facilities is done in order to handle the actual waste characteristics. For example, the incinerator in Högdalen is designed to burn waste with a minimum average heating value on a wet base of 10 MJ/kg and the new facilities will feature the same characteristic (Lindman 2012). The heating value of the waste depends on its composition and right now the fractions with poor calorific value (e.g. food waste, 40% share of mixed waste in Sweden today) are balanced by fractions with higher heating value (e.g. plastic and paper packaging waste fractions, 30% share of mixed waste in Sweden) that are not sorted properly for recycling by the households (Avfall Sverige 2011) and by industrial waste (mix of plastic, wood and paper) (Fortum AB 2011).

Although incinerators have quite robust performances and quite wide range of operation, the waste should have certain characteristics in order to ease the combustion and avoid the overutilization of auxiliary fuels (usually fossil fuels). The combustibility of waste is influenced not only by the heating value, but also by the moisture content and the shares of the combustible fraction and of the ashes (Rand et al. 2000). The most important parameter is the moisture level, which, if too high, not only leads to the use of more fuel to support the combustion, but also requires more air during the combustion and therefore involves lower temperature of the exhaust gases and worse characteristics of the steam for the electricity production (Worrell & Vesilind 2012). A change in the waste generation or in the waste sorting can therefore strongly influence the behaviour of these facilities in terms of energy production. Therefore it might be of interest to investigate the effects of likely changes in the future waste composition on the incinerators’ operations, above all considering the fractions that are heavily affecting the combustion of the waste, of which the most important is the plastic waste (in Figure 1 the contribution of the major waste fractions to the energy generation in the incinerators is shown).
This can be even more relevant expanding the boundaries of the study outside the single operation of the incinerators, considering also the fate of the waste that is collected for recycling. Recycling and incineration have clearly different outcomes. Using the same input (plastic waste), the former is providing secondary raw materials that will hopefully replace virgin ones (mainly fossil fuels), while the latter generates electricity and heat. In this clash the legislators try to regulate the flows towards incineration and recycling, setting up targets for the amount of recyclable waste that should be collected. In particular, with the revised Waste Framework Directive, the European Commission wants people to sort at least the 50% of the household waste in 2020 (Directive 2008-98-EC).

However, considering all the waste fractions together, the legislation does not fix specific constraints on the different waste fractions for the achievement of the target. Therefore, without adding other rules, the waste handling can assume very diverse configurations, produce very different outputs and still comply with the legislation. For example, since the plastic waste represents less than the 15% of the total waste generation from households (Silfverduk & Carlberg 2011), the target of the 50% of recycling of household waste can be achieved almost regardless of the plastic waste handling. However this would not have negligible effects on the waste incineration, being the contribution of plastic waste to the energy production very important.

Figure 1 – Contribution of the major waste fractions in the mixed household waste to energy generation in the incineration facilities in the County of Stockholm for the year 2011. The plastic fraction is the most important one. Figure obtained from pickling analysis (Silfverduk & Carlberg 2011) data and waste fractions heating values.
because of its high heating value and low moisture level (see Table I in Appendix I - Specific Data Sources). Neither this would have insignificant effects on the environment in terms of non-renewable resources use, both for energy and plastic production. The investigation of these effects is the purpose of this study.

Lately the household waste handling has been the subject of several studies, especially after the focus set by the European Commission on this subject. The waste hierarchy, which is giving a higher environmental profile to recycling than energy recovery, has been demonstrated to be valuable just as a rule of the thumb and not applicable in general because of its dependence on local settings of the system, which are:

- Technology for incineration and recycling;
- Energy sources;
- Materials substituted with secondary raw materials.

One reviewed study compares recycling and incineration of paper waste and shows the importance of the recycling technologies in the evaluation of the global warming potential. For example a combination of good incineration technology (high efficiency in energy production) and average recycling process (high energy use and low material recovery efficiency) can yield to a lower global warming potential for incineration in comparison to recycling (Merrild et al. 2008).

Another study highlights how the situation becomes even more complex considering plastic waste. While recycled paper is usually used back again in applications similar to the original ones, thus substituting virgin raw materials (wood), recycled plastic can be used also to substitute other materials. This implies different effects on the environment. For instance the energy balance and the carbon footprint of plastic recycling become less advantageous when the secondary raw materials are substituting wood. In fact in this way the possibility of replacing virgin raw materials, which could allow the saving of fossil fuels for the production of new plastic, is lost in less noble applications, for which renewable material resources could be used (Finnveden et al. 2005).

However the virgin raw materials are irreplaceable if the recycling process cannot sort properly the different polymers that are making up the mixed plastic waste stream, yielding in low quality input for the recycling facilities. This is shown in detail in other two reviewed studies, one focused on the recycling processes, showing outcomes, energy uses and material efficiencies of several technologies (Shonfield 2008) and the other one on the plastic waste handling from a system perspective (Carlsson 2002).

The fact that this topic has already been studied does not mean that there is no need of further investigations. The system is evolving continuously and the previous studies are useful to give a structure for the new ones, but the results need to be updated. Other studies have been reviewed before starting the project, but the four mentioned in the previous paragraphs are the ones that
have mainly inspired this one. The main change applied in this project regards the boundary conditions considered. In fact, while in the cited studies the changes in the waste generation and the waste handling are not considered together, these variations are both taken into account in this study. Another change regards the methodology, since this work does not rely on any life cycle assessment tool. This choice was driven by the willingness of tailoring the tool on the system’s characteristics.

Burning plastics means producing energy at the cost of the fossil fuels that have to be used again to produce the new plastics, while recycling plastic can potentially lower the non-renewable resources use for the production of virgin plastics (just if the recycled plastic actually replaces the virgin one) at the cost of the energy for the reprocessing. In both the processes energy and material are involved. Therefore, combining different waste handling strategies regarding incineration and recycling, different outcomes in terms of energy and material can be obtained. The fact that the virgin raw materials for plastic are also a combustible, allows even an aggregated evaluation just in terms of energy, which facilitates the comparison of the possible waste handling systems. Considering a constant fossil fuels use, a maximisation of the energy production should be pursued.

Hence, the tool built is a model based on material, energy and fossil fuels use accounting. In particular, the model is used to evaluate the performances of different scenarios in which the key parameters are varied to represent the most likely or interesting future configurations, based on available forecasts on waste generation and handling. Although the whole plastic waste fraction is modelled, the focus is mainly on the plastic packaging, because of its large share in the global plastic usage (Mudgal et al. 2011) and because of the availability of data. This data is mainly reported by FTI AB, the company that manages the waste under the Producers’ Responsibility. However, the performances of the incinerators, in terms of operability, are not only influenced by the plastic fraction. Therefore all the fractions that are building up the mixed combustible waste have to be considered. Nevertheless, of these latter just the changes in generation and diversion from combustion are taken into account, while for the former the boundaries are expanded to account for the effects of recycling.
Aims and Objectives

The introduced project has the aim to investigate, in a time frame of 20 years, the performances of the facilities involved in the plastic waste handling (incinerators and recycling plants) considering both the future possible changes in mixed waste generation and in the plastic waste handling itself, in order to highlight the configurations of the system to be avoided and the ones to be pursued. The performances are evaluated in terms of fossil fuels saving or depletion and energy balances (electricity and heat) in respect to the current setting.

The specific objectives of the study are:

- Analyse the actual waste management system in the County of Stockholm to define the main stakeholders and the key parameters;
- Forecast the likely changes in the next 20 years regarding waste generation, handling and the previous depicted boundary conditions, in order to define interesting scenarios to be modeled and evaluated;
- Build a model that evaluates the performances (in terms of energy generated and fossil fuels used for the plastic production) of the considered plastic handling strategies following the chosen criteria, trading off availability of data and need of data;
- Feed the model with the selected scenarios to show the potentialities of the modelling and to find, among the ones considered, the best coupling of plastic waste generation and handling system following the set evaluation criteria.
Methodology

The methodology has been developed in accordance to the aim and objectives of the study. Each part of the study required a different approach depending on its characteristics. The first two objectives did not demand any special research technique, being their accomplishment mainly based on literature review. The analysis of the actual waste management system has been based on legislation, institutional reports and interviews with the stakeholders involved. Similarly the forecasts of the future changes in the waste generation and handling system, to select the scenarios to be evaluated, have been obtained from sectorial studies, stakeholders’ predictions and expectations. However, the part of the study that requires a deeper explanation is the modelling part, which is the one that eventually yields in the results of the study.

Waste Input-Output Modelling

Modelling is the medium through which the evaluation of the possible future outputs of several waste management settings, considering the variability of the waste generation (starting from the actual scenery of the County of Stockholm), is carried out. The modelling is not done in order to follow in principle any standard assessment method, like the classical Environmental System Analysis tools (Life Cycle Assessment, Integrated Sustainability Assessment, etc.) but just to produce the desired results, which are the energy generated by incineration and the fossil fuels used for the plastic production, as stated in the objectives.

The parameters and the outputs considered in this analysis have been chosen in order to trade-off data availability and interests of the major groups of stakeholders related to the waste management system, which were investigated during the interviews and are explained in the Waste Management System Analysis chapter. Therefore, even though the life-cycle thinking is applied, the parts of the system modelled are just the ones that the stakeholders can effectively influence. For example, the stakeholders in the waste management system can hardly influence the consumption patterns, while they can directly affect the way in which waste is used and treated, affecting the amount of energy generated and of material recovered within the system. In this framework, the waste is considered as the input, and the upstream processes are not modelled.

Relevance is given to the fossil fuels used for plastic production turnover and to the energy (heat and electricity) balance between the energy generated from the incineration of plastic waste and the energy used for the recycling process. A reduction in the fossil fuels use can be seen as a step in the direction of sustainable development (Goedkoop & Spriensma 2001) and this is confirmed by the willingness of the County and of the City of Stockholm to approach a zeroing of the use of fossil fuels in the year 2050 (Stockholm Stad 2012). However a reduction of fossil fuels use can be achieved only with an improved recycling that affects the energy generation and consumption (since less plastic can be used as fuel in the incinerators and more has to be reprocessed in the
recycling plants). Hence most likely no scenario among the others will have the highest energy generation and lowest fossil fuels use for plastic production, hindering a clear evaluation of the different scenarios. To ease this part of the process, the variation in fossil fuels use, in respect to the current system performances, is assumed to be used in (if negative) or removed from (if positive) the energy generation from fossil fuels. Therefore the evaluation of each scenario will be summarised just with the values of energy generation (electricity and heat) at constant fossil fuels use. In Figure 2 the evaluation scheme is illustrated.

Gathering of data

The data used in the study was mainly collected from reports prepared by the organisations acting in the waste management system at different societal levels. The documents produced by the municipalities in the County of Stockholm were used above all for the data on waste generation and diversion for recycling, while the documents drawn up at national and European level were useful to understand the legislative framework regarding the waste handling. The data filling up the technological background in the plastic recycling come mainly from previous studies in the field since the companies working in this field have not answered to the questions forwarded. Other data and information were gathered during interviews with the stakeholders (e.g. City of Stockholm, FTI AB, Fortum AB, Fiskeby AB, II Recycling AB). The specific sources for the different data are detailed in the Appendix I - Specific Data Sources.
Waste Management System Analysis

After having broadly explained the structure of the work, the field research can be now illustrated, starting from the analysis of the current waste management system in the County of Stockholm. This is needed to give relevance to the kind of approach chosen in this study, to justify the evaluation criteria and target the right audience. Therefore, in the following subchapters:

- The spatial and temporal boundaries of the system analysed are described;
- The stakeholders involved in the considered system are listed, explaining their interconnections, their respective concerns and priorities.

This analysis is establishing a good base also for the selection of the scenarios. In fact, the current structure of the system leads not only to the present functioning but also to the future decision-making that will influence the future plastic waste handling. Finally a good knowledge of the system is needed to build up a model that produces interesting and understandable results for the stakeholders.

Before exploring the details of the analysis, an overview of the plastic waste streams, shown in Figure 3, can be useful in order to correlate afterward system boundaries and the different actors to the different waste handling functions.

Figure 3 - Overview on the plastic waste streams, starting from the households, who generate the plastic waste, and arriving to the final treatment, that can be incineration or recycling depending on sorting or not sorting of the plastic waste by the households.
**Spatial Boundaries**

As anticipated before and as shown in Figure 3, incineration and recycling are the two main processes to be considered in the plastic waste handling. For the incineration of mixed household waste, the boundaries are traced to include just the County of Stockholm. This is because the incinerators situated in the County of Stockholm are mainly powered with the household waste generated in that area (Fortum AB 2011) and because the main outputs of these incinerators are used locally. The electricity produced is delivered to the national network, but it is contributing mainly, for geographical reasons, to the electricity supply of Stockholm, while the heat generated is used in the district heating network of Stockholm.

In contrast, for the recycling process, the geographical boundaries cannot be defined precisely. This is because FTI contracts the recycling facilities that let them set the lowest prices for the producers for the management of the packaging waste. These facilities can be in the Swedish territory, in other European countries or even in India or China (Nilsson 2012). Hence, since different destinations for the plastic waste are possible, the boundaries have to be flexible and the outputs (secondary raw materials, electricity and heat from the incineration of the residuals in waste-to-energy facilities close to the recycling plants) have to be accounted on a global scale. In Figure 4 the spatial boundaries are summarised.

![Figure 4 – Summary of spatial boundaries related to incineration and recycling of plastic waste](image)

**Temporal Boundaries**

The study is aiming to evaluate the performances and the outputs of the considered system in the year 2030. Such medium-long term analysis could be useful for a thoughtful planning of the upcoming regulations. In fact, in the considered timeframe, the expected or influenceable changes in the inputs can be still previewed with a certain level of meaningfulness and other elements, as for example the existent or foreseeable future facilities in the waste management panorama, will unlikely experience radical changes and therefore they can be considered as constant in the modelling. A 20 years temporal frame was considered also in some reviewed forward-looking studies that have been used as source for predictions about possible future changes in the waste management system (Johnson 2010).
Stakeholders Involved

After having defined the boundaries of the system, the stakeholders that are operating in this frame have to be considered. In the waste management system several actors with quite diverse background and interests are playing. Although the laws to be enforced are set up by the Swedish Government, the structure and the splitting of the responsibilities are similar to the ones in the other countries that are part of the European Union, since they have evolved in consequence of the legislation decreed at that level, legislation of which the last version is identified by the Waste Framework Directive (Directive 2008-98-EC).

The mixed household waste is under the responsibility of the municipalities, which have to set up the collection and handling system, contracting companies that are designed to accomplish these functions. The most important actor here is Fortum AB, the energy company (of which 9% is owned by the City of Stockholm, (Lindman 2012)) that owns the incinerations facilities in the County of Stockholm. On the contrary, a big fraction of the recyclable waste generated by households, the packaging waste, is under the responsibility of FTI AB, which is an organisation owned and set up by the producers of goods that are using packaging for their products. This company started in 1994 in order to comply with the national and regional regulations (Directive 94-62-EC 1994). Similarly to what the municipalities are doing for the household waste, FTI AB has to contract collectors and recycling facilities to handle the packaging waste from households. In Figure 5 the situation is summarised.

![Diagram of waste management system]

In the overall organisation there is also a complex monitoring system, which reports data on the current waste management system to the governmental organisations at the different societal levels, starting from the municipalities and reaching the European Union. The most important ones are Avfall Sverige, Naturvårdsverket (the Swedish Environmental Protection Agency SEPA) and the Waste Council. This data is not useful only for the governments but also for the academia, which can elaborate the available information to formulate indications for the future decision-making. In Table 1, the main stakeholders are summarised, with the related field of action.
Table 1. List of stakeholders involved in the waste management system

<table>
<thead>
<tr>
<th>Societal Level</th>
<th>Stakeholder</th>
<th>Field of Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>National/Regional</td>
<td>European Union</td>
<td>– Legislation (heralding of directives)</td>
</tr>
<tr>
<td>governments</td>
<td>Swedish Government</td>
<td>– Legislation (setting of the actual system to comply with the EU directives)</td>
</tr>
<tr>
<td>Local governments</td>
<td>Municipalities in the County of Stockholm</td>
<td>– Management of Household Waste</td>
</tr>
<tr>
<td>Industry</td>
<td>FTI AB</td>
<td>– Management of Recyclables under the Producers’ Responsibility</td>
</tr>
<tr>
<td></td>
<td>Incinerators’ owners (e.g. Fortum AB)</td>
<td>– Treatment of Household Waste</td>
</tr>
<tr>
<td></td>
<td>Recycling companies (e.g. Swerec AB)</td>
<td>– Recycling of sorted waste</td>
</tr>
<tr>
<td>National organisations</td>
<td>Avfall Sverige, Naturvårdsverket (SEPA), Waste Council</td>
<td>– Help and monitor municipalities</td>
</tr>
<tr>
<td></td>
<td></td>
<td>– Environmental Protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>– Advisory organisms</td>
</tr>
<tr>
<td>Academia</td>
<td>Universities (e.g. KTH), Research Institutes (IVL)</td>
<td>– Technological Support</td>
</tr>
<tr>
<td>Individuals</td>
<td>Households</td>
<td>– Waste generation and sorting for recycling</td>
</tr>
</tbody>
</table>

**Concerns and Priorities of the Stakeholders**

Although the different stakeholders are working and contributing to build up the same system, each of them has a particular perspective, which results in a wide range of concerns and priorities. These prerogatives are the forces that drive also the decision-making of the stakeholders and that eventually are determining the future setting of the waste management system. Therefore, to predict the possible futures, the twigging of these concerns and priorities is needed. In this perspective, it can be helpful to consider the inputs and the outputs of the different treatment options for plastic waste. In Figure 6, the entries and the outcomes of the main waste handling options for plastic waste are shown.
Figure 6 – Inputs and outputs for incineration and recycling of plastic waste. The incineration of plastic waste produces energy in the forms of electricity and heat, while the recycling process, powered with a certain amount of energy yields in secondary raw materials. The recycling process has usually residuals, which are commonly incinerated.

Focus of the stakeholders managing the mixed household waste

Considering the management of mixed household waste, the municipalities care mainly about the accomplishment of the processing of waste to reduce its effect on health and environment. The fact that the incinerator in Högdalen supplies energy (mainly heat but also electricity) to the City of Stockholm involves an overlapping of this perspective with the one of the incinerator’s owner, Fortum AB (Dahllöf & Personne 2012). Fortum AB has obviously a particular concern regarding the waste supply from the municipalities, in order to be able to run the incinerators in the best possible way. A constant supply of waste, with homogeneous characteristics, allows a good planning of the operations of the incineration facilities, yielding in an efficient energy production management. Waste can be considered as fuel for the incinerators. If the fuel provided is not enough or of bad quality (low heating value, high moisture content), the energy production (heat and electricity) is evidently affected. Fortum AB already relies on several sources to grant the right supply of waste, but the County of Stockholm is clearly the main reservoir, and changes in the local waste generation of waste can affect the energy production (Lindman 2012).

This is the reason why the overall waste composition has been considered in the study. The focus of the study is on plastic waste, but, as hinted in the introduction, the incineration of waste is carried out on the mixed waste, of which the plastic waste is just a fraction. If only the plastic waste was considered it would not be possible to assess the performances of a particular incineration facility, since it would imply the assumption that the incineration process is not influenced by the waste composition, which is not the case (see Figure 1). This is because each waste fraction has specific characteristics that strongly affect the combustion process. These characteristics are:

- Average heating value (AVG HV);
- Moisture content (M);
Knowing the exact composition of the mixed waste it is possible to know the average values of these characteristics for the mixed household waste. This helps in understanding if the combustibility of the waste requires auxiliary fuels (Rand et al. 2000). The exact estimation of the auxiliary fuels to support the combustion was not found in the literature; therefore no precise assessments can be made on this quantity. However it is possible to state if auxiliary fuels are constantly needed or not (Rand et al. 2000). In particular, auxiliary fuels are added if, considering the average properties of the waste, one of the following conditions occurs:

- Combustible fraction $CF \leq 25\%$;
- Moisture content $M > 50\%$;
- Ash content $A > 60\%$.

If these conditions are satisfied but the average heating value is below the design one, oil might also be added in order to increase anyway the quality of the waste. This last addition would be done mainly to guarantee that the waste to incineration facility is producing at least the designed amount of energy (heat and electricity) since it is unlikely that the average heating value is reaching a value below the one that allows the combustion of waste (7 MJ/kg on a dry base, (Rand et al. 2000)).

**Focus of the stakeholders managing plastic waste sorted for recycling**

Considering instead the plastic sorted for recycling, the company set by the producers, FTI AB, is just following the directives and has no particular concerns regarding the fate of the recyclables. The organisation has the main objective of setting up the easiest and least expensive system for the producers, respecting the targets on collection of recyclables set at the European (by the European Commission) and Swedish (by SEPA) level (Nilsson 2012). This might be because the quality level of the recyclables is quite low and therefore the producers are not interested in recovering them for their manufacturing processes, differently from what happens for the packaging for beverages collected separately by Returpack, where the collected material has high quality and can be recovered efficiently (Returpack 2012).

The recycling facilities, to which the recyclables are sold by FTI, are the ones that have eventually to deal with the transformation of the waste collected for recycling. Unfortunately, none of the plastic recycling companies contacted showed willingness to cooperate and for this reason their perspective has been conjectured analysing previous studies. The speculation has been helped by an interview with one paper recycling company, Fiskeby AB. In this last case the processes are quite different from the plastic recycling, but the position in the market, the constraints and the aims of this kind industry are not very different from the ones of a plastic recycling company. Therefore, this workaround at least helps in defining roughly concerns and priorities of this part of the industry.

For a recycling plant, amount and the quality of the material received are fundamental parameters. Similarly to the incinerators and to any other kind of industrial plant, also a recycling plant has a
certain treatment capacity, which has to be filled in order to justify the size of the plant itself (De Magistris 2012). However, differently from the paper recycling, in which different inputs (different quality grades for the paper waste) are used concurrently to produce just one final product (recycled paper for new packages), in the plastic recycling only one input, the mixed plastic from households, where plastic with different compositions are mixed, has to be processed to get again the single polymers (LDPE, HDPE, PET, PV, PVC, PP, PS, Others) separated. This allows the proceeding with the re-melting phase, to have new plastic pellets to be used in the production system. In Figure 7 the recycling process is summarised to show this single input/multi output feature.

![Figure 7 – Diagram on the plastic recycling process, having plastic waste with mixed composition as input and the different polymers again separated as output.](image)

The separation step represents a significant complexity, above all considering the degree of mixing of the plastic waste from households. This does not mean only an increased energy use along the processing, but also a risk of losing part of the material, if wrongly sorted. On the other hand, just a small contamination of one polymer with other polymers can ruin the whole upstream processing during the re-melting step (Carlsson 2002). Hence, the quality of the input and the efficiency in recovering the material determines the amount of secondary materials available at the end of the recycling process. Also the potential use of these secondary raw materials is influenced by these parameters. The fact that Swerec AB, one of the main recycling company for mixed plastic waste, has the flower pots production as one of the main uses of their secondary raw materials (Swerec 2012), while Cleanway PET Svenska AB, the recycling company for the PET bottles, recycles the material back in the bottles production (Returpack 2012), is a clear example.

In Appendix III - Model for Recycling Process, a clearer explanation of these phenomena is illustrated. The recycling process is considered in the detail to extract the outcomes needed for the purpose of evaluating energy consumption and material efficiency, which are:

- The electricity consumption during the recycling operations per mass of plastic collected \( (EL/forREC \text{ pmp}) \);
- The material loss coefficient \( (MLC) \), which represents the portion of the plastic collected that is lost during the recycling process, e.g. during the sorting phase;
- The virgin plastic substitution coefficient (VPSC), which represents the portion of the plastic recycled that is actually used to replace plastics produced with virgin raw materials.

**Focus of the stakeholders influencing the overall waste management system**

Similarly to what happened with the plastic recycling companies, even contacting the high societal level stakeholders did not yield to significant results. However these stakeholders have hopefully as main focus the sustainable development of the waste management system itself. Therefore the waste is seen more and more as something to be used efficiently again in the production system following the principles of industrial ecology (Singh et al. 2008). In this picture, the universities and the research institutes have the charge of giving directions to make possible the desirable sustainable development.

**Justification of the evaluation criteria**

After having analysed the system and the perspectives of the different stakeholders, the evaluation criteria introduced in the methodology section actually manifest their meaningfulness. Energy and secondary raw materials, which are connected strictly with the fossil fuels use, are the most important outputs of the plastic waste handling. The stakeholders have shown to be interested in tracking the trends of these outputs in the next years, having the willingness to improve and increase (if valuable) or reduce them (if they represent a burden). At the same time the evaluation criteria can be easily combined together, by means of the constant fossil fuels use hypothesis, to evaluate the general development of the plastic waste management system in terms of energy recovered at the end of the processes. In Figure 8 the reasoning throughout this section is summarised schematically.

Figure 8 – Overview on concerns and priorities for the different groups of stakeholders and correlation of these driving forces with the chosen evaluation criteria.
Possible future changes and scenarios selection

Thanks to how the work has been structured, the modelling does not only aspire to reproduce the current system performances, but also to evaluate the future ones, considering changes both in the waste generation and in plastic waste handling. Hence, to pursue the established aim of the study, after having analysed the plastic waste management in the County of Stockholm the likely changes in this system, in the next 20 years, have to be predicted. As mentioned in the section regarding concerns and priorities of the stakeholders are responsible concurrently of the evolution of the system. Being different (and sometimes in contrast) the driving forces imposed by the different stakeholders, there are infinite possible futures. From this set of futures, some particular scenarios can be extracted to exemplify situations certain groups of stakeholders succeed in influencing the evolution more than the others, thus leading to improvements relatively to particular interests and overall effects to be investigated.

To produce the desired outputs, each scenario needs a series of inputs, which can be grouped in the following categories:

- **Waste generation**: the waste generation accounts for the amounts of waste produced in each waste category, usually classifiable by material origin (e.g. organic/food waste, paper waste, plastic waste, etc.). Being plastic waste the focus of this study, the plastic waste generation is divided also by polymer. This characterisation is fundamental for the recycling plants, depending the recycling process on the plastic waste composition;

- **Waste collection and treatment organisation**: this group refers to the way in which the waste handling is organised, starting from the collection system and ending in the treatment phase, which determines the outputs of the waste management system. In this study only variations in the plastic waste handling are considered. The treatment and the related outputs are strictly connected to the collection, being the separation stage in the recycling process one of the most important in determining the secondary raw materials’ quality;

- **Waste sorting rates**: despite the handling system designed by the stakeholders managing the waste management system, the collection rates for the sorted fractions can be set to different levels by the legislators.

The objective now is to select meaningful scenarios to evaluate. The grouping of the inputs helps in generating the scenarios. In fact each combination of the different variations of these inputs can be taken as possible future for the plastic waste handling system. To simplify the choice, just two possible settings per each category are considered. Considering the waste generation, the inputs are differentiated just in the plastic waste generation. In one setting the generation is adapted, in terms of composition, to the recycling processes, which means that the polymers easily recyclable are used more extensively than the others. The polymers that have shown better fit to the recycling processes are HDPE, LDPE, PP and PET (Shonfield 2008). In the other setting the generation goes in the opposite direction, with an increased share of the other polymers. However in both the settings
the overall amount of plastic waste is constant, and it is taken as increased in respect to the current situation, following the forecasts in one of the reviewed studies, which previews an increase above 20% in less than 10 years (Mudgal et al. 2011).

Proceeding with the waste collection and treatment, the collection can be separated for certain polymers or mixed, putting together all the types of plastic waste produced by the households. Sequentially, the processes are organised to comply with the collection system, with low energy consumption and high material efficiency (low residuals and good quality of the secondary raw materials) for the separated polymers, and with reversed features for the mixed collection. Finally the waste sorting rates in the different scenarios can be either high (70-90%) or low (20%). In Figure 9 the settings in the three inputs categories considered are represented schematically.

Figure 9 – Possible settings in the different group of inputs to produce the scenarios to be evaluated in the study.

These set of inputs would already lead to 8 possible scenarios. However some combinations of these different inputs are less likely than others. For example, the coupling of mixed waste collection and plastic waste generation adapted to the recycling process is very unlikely, since the recycling process in this case would be designed to handle a mixed plastic stream and there would not be any specific recycling process that the waste generation should adapt to. Moreover, the separated collections lead rarely to low sorting rates and therefore this combination is not explored in this study. In this way the scenarios to be considered, summarised in Table 2, are 4.

Table 2. Overview on Scenarios selected for evaluation starting from the considered groups of inputs.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Not adapted to the recycling process</td>
<td>For Mixed Plastic</td>
<td>Low</td>
</tr>
<tr>
<td>Adapted to the recycling process</td>
<td>For separated polymers</td>
<td>High</td>
</tr>
<tr>
<td>Not adapted to the recycling process</td>
<td>For Mixed Plastic</td>
<td>High</td>
</tr>
<tr>
<td>Not adapted to the recycling process</td>
<td>For separated polymers</td>
<td>High</td>
</tr>
</tbody>
</table>
The other inputs needed to run the model, the ones about the generation and handling of the other waste fractions are kept constant in these 4 scenarios. Some of them are assumed to have the same exact value of the current situation (and this is not valid just for the waste fractions composing mixed household waste, but also for the industrial waste that is burnt together with the household waste), while others have been updated in respect to the current setting (evaluated in Appendix II - Waste Generation and Sorting - Base Case Evaluation), in order to try to represent the future conditions. The changes applied are listed here:

- Collection of recyclables organised to make the households sort waste in function of the material. Therefore not only the packages are collected for recycling. This accounts for a very likely change in the future waste management system (Naturvårdsverket 2009);
- Sorting of food waste spread among the population. The expansion of the current food waste collection is already planned (P. Nyström 2012). The level of food sorting is assumed to reach the 50%;
- Increased efficiency for electricity production for the incinerators. This consideration comes from the features of the new incinerators that will start to operate soon in Brista (Lindman 2012);
- Decrease in newspapers waste generation, following the trend of the last years, in which the newspapers have decreased of roughly 10% each year (FTI AB 2012). Globally in the next 20 years the variation is assumed to be a 60% decrease.

Considering again the 4 scenarios, of course these 4 combinations are a very limited selection of the possible ones, but they can already be useful to test the evaluation system set up in this project and in giving results interesting for the stakeholders. This is because the different scenarios can be linked to different combinations of decisions made by the stakeholders.

**Scenario 1 – Current Plastic Waste Handling Setting with future waste generation**

The Scenario 1 considers a plastic waste handling similar to the current one, with mixed plastic waste collection and low recycling rates for the plastic waste (see Appendix II - Waste Generation and Sorting - Base Case Evaluation). However the waste generation is updated as just explained. This scenario could happen if no big changes in the legislation are performed and if the interest in the secondary raw materials remains at low levels. In this way the incinerators could keep taking advantage of the plastic waste contained in the mixed household waste and would not have any reason to steer the decision-making in other directions.

**Scenario 2 – Agreement among production and plastic recycling system**

The Scenario 2, featuring a completely different plastic waste handling system, which collects separately the polymers that are easier to recycle, exemplifies an agreement among producers and recyclers in order to improve the amounts and the quality of the secondary raw materials. This
would allow the use of these secondary raw materials back in the production system in uses similar to the original ones, thus actually substituting virgin raw materials. This scenario could occur with the concurrent help of the legislation and of the academia, repeating a phenomena already happened with the deposit system for the aluminium cans and PET bottles for beverages containers, for which a separate collection system has been set following the Swedish rules (SFS 2005:220 - Förordning om retursystem för plastflaskor och metallburkar). Consequently the recycling process of these waste fractions evolved to match the collection system. Considering specifically the PET bottles, a new recycling technology allows currently to obtain food contact grade secondary raw materials and therefore an higher substitution of virgin plastics (Veolia 2012).

**Scenario 3 – Current handling system with high sorting rates forced by the legislation**

The Scenario 3 illustrates a condition in which the legislation (at European or national level) requests higher collection rates for the plastic waste for recycling, without promoting any change in the collection and treatment phases. This could affect heavily the incinerators, since the supply of plastic waste would decrease dramatically. Among the other scenarios, this is less likely, because it would imply a strong influence of the regional governance, not coupled with the will of any other stakeholder, except for the recycling facilities, that would have to face anyway an increased offer in the secondary raw materials market also from the other countries. However, considering that the major treatment option for plastic waste in the European Union is still landfilling (reference), a policy that requires increased recycling even without precise further indications cannot be excluded.

**Scenario 4 – Collection organised by polymer without agreement with the production system**

The Scenario 4, considering a waste handling system and sorting rates equal to Scenario 2, but production system not coupled with the recycling one, illustrates a situation in which the producers give more value to a broader choice in the packaging solution to the possibility of using secondary raw materials. The comparison of Scenario 2 and Scenario 4 can help an evaluation of the resilience of a more complex and structured handling system organised by polymer.

**Numerical Derivations of Scenarios**

Before going further in the details, specifying the numerical implications of the described scenarios, the results of the Base Case evaluation (see Appendix II - Waste Generation and Sorting - Base Case Evaluation) are needed to set clearly the root of all the possible scenarios. In Table 3 the derived waste generation and sorting rates are illustrated divided for waste fractions, while the results from the evaluation of the recycling process (see Appendix III - Model for Recycling Process) are shown in Table 4.
Table 3. Waste Generation and Sorting in the current situation (Base Case) expressed for each waste fraction. The values come from the analysis of the mixed household waste (see Appendix II - Waste Generation and Sorting - Base Case Evaluation).

<table>
<thead>
<tr>
<th>Waste Fraction</th>
<th>Total Dry Generation (kg/pers/year)</th>
<th>Sorting Rates %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic Packaging - LDPE</td>
<td>5.8</td>
<td>17%</td>
</tr>
<tr>
<td>Plastic Packaging - HDPE</td>
<td>3.4</td>
<td>17%</td>
</tr>
<tr>
<td>Plastic Packaging - PET</td>
<td>0.7</td>
<td>17%</td>
</tr>
<tr>
<td>Plastic Packaging - PP</td>
<td>3.4</td>
<td>17%</td>
</tr>
<tr>
<td>Plastic Packaging - PS</td>
<td>1.6</td>
<td>17%</td>
</tr>
<tr>
<td>Plastic Packaging - PVC</td>
<td>0.5</td>
<td>17%</td>
</tr>
<tr>
<td>Plastic Packaging - Others</td>
<td>0.5</td>
<td>17%</td>
</tr>
<tr>
<td>Other Plastics - Mixed</td>
<td>6.6</td>
<td>0%</td>
</tr>
<tr>
<td>Food</td>
<td>36.2</td>
<td>0%</td>
</tr>
<tr>
<td>Newspapers and office paper</td>
<td>49.0</td>
<td>79%</td>
</tr>
<tr>
<td>Paper Packaging</td>
<td>21.9</td>
<td>34%</td>
</tr>
<tr>
<td>Other Paper</td>
<td>9.1</td>
<td>0%</td>
</tr>
<tr>
<td>Textiles</td>
<td>3.2</td>
<td>0%</td>
</tr>
<tr>
<td>Others</td>
<td>9.0</td>
<td>0%</td>
</tr>
<tr>
<td>Garden Waste</td>
<td>2.3</td>
<td>0%</td>
</tr>
<tr>
<td>Glass Packaging</td>
<td>36.1</td>
<td>75%</td>
</tr>
<tr>
<td>Other Glass</td>
<td>1.4</td>
<td>0%</td>
</tr>
<tr>
<td>Metal Packaging</td>
<td>3.7</td>
<td>30%</td>
</tr>
<tr>
<td>Other Metal</td>
<td>1.1</td>
<td>0%</td>
</tr>
<tr>
<td>Inert Waste</td>
<td>4.4</td>
<td>0%</td>
</tr>
<tr>
<td>Others</td>
<td>7.2</td>
<td>0%</td>
</tr>
<tr>
<td>Haz./el. Waste</td>
<td>1.9</td>
<td>0%</td>
</tr>
<tr>
<td>Industrial Waste</td>
<td>43.0</td>
<td>0%</td>
</tr>
</tbody>
</table>
Table 4. Collection System, Electricity Use, Material Loss Coefficients and Virgin Plastic Substitution Coefficients for all the plastic waste fractions in the current situation (Base Case). The values come from the analysis on the recycling process (see Appendix III - Model for Recycling Process)

<table>
<thead>
<tr>
<th></th>
<th>Collection</th>
<th>Electricity Use (MJ/kg)</th>
<th>Material Loss Coefficient (%)</th>
<th>Virgin Plastic Substitution Coefficient (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic Packaging- LDPE</td>
<td>Mixed</td>
<td>1.50</td>
<td>20%</td>
<td>60%</td>
</tr>
<tr>
<td>Plastic Packaging - HDPE</td>
<td>Mixed</td>
<td>1.50</td>
<td>30%</td>
<td>60%</td>
</tr>
<tr>
<td>Plastic Packaging - PET</td>
<td>Mixed</td>
<td>1.50</td>
<td>30%</td>
<td>60%</td>
</tr>
<tr>
<td>Plastic Packaging - PP</td>
<td>Mixed</td>
<td>1.50</td>
<td>30%</td>
<td>60%</td>
</tr>
<tr>
<td>Plastic Packaging - PS</td>
<td>Mixed</td>
<td>0.20</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Plastic Packaging - PVC</td>
<td>Mixed</td>
<td>1.50</td>
<td>30%</td>
<td>60%</td>
</tr>
<tr>
<td>Plastic Packaging - Others</td>
<td>Mixed</td>
<td>0.20</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Other Plastics - Mixed</td>
<td>NO</td>
<td>1.50</td>
<td>30%</td>
<td>60%</td>
</tr>
</tbody>
</table>

From the Base Case, the data on plastic waste generation for the two selected settings (adapted or not adapted to the recycling process) are varied in percentage as expressed in Table 5.

Table 5. Variations of the Plastic Waste Generation in respect to the Base Case. In between brackets are listed the scenarios in which a certain particular setting is used.

<table>
<thead>
<tr>
<th></th>
<th>Not Adapted to Recycling Process (1,3,4)</th>
<th>Adapted to Recycling Process (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic Packaging- LDPE</td>
<td>-20%</td>
<td>40%</td>
</tr>
<tr>
<td>Plastic Packaging - HDPE</td>
<td>-20%</td>
<td>40%</td>
</tr>
<tr>
<td>Plastic Packaging - PET</td>
<td>-20%</td>
<td>40%</td>
</tr>
<tr>
<td>Plastic Packaging - PP</td>
<td>-20%</td>
<td>40%</td>
</tr>
<tr>
<td>Plastic Packaging - PS</td>
<td>30%</td>
<td>5%</td>
</tr>
<tr>
<td>Plastic Packaging - PVC</td>
<td>30%</td>
<td>-100%</td>
</tr>
<tr>
<td>Plastic Packaging - Others</td>
<td>1000%</td>
<td>5%</td>
</tr>
<tr>
<td>Other Plastics - Mixed</td>
<td>20%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Considering instead the waste collection and treatment, for Scenario 1 and 3 the values to be used are the ones expressed in Table 4 (constant in respect to the Base Case), while for Scenario 2 and 4, which perform a separate collection of plastic waste sorted for recycling, the values to be used are shown in Table 6.
Table 6. Collection System, Electricity Use, Material Loss Coefficients and Virgin Plastic Substitution Coefficients for all the plastic waste fractions for the setting that is considering separate collection for a few polymers that are composing the plastic waste (for Scenario 2 and 4).

<table>
<thead>
<tr>
<th>Plastic Packaging</th>
<th>Collection</th>
<th>Electricity Use (MJ/kg)</th>
<th>Material Loss (-)</th>
<th>Virgin Plastic Substitution (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDPE</td>
<td>Separate</td>
<td>1.50</td>
<td>15%</td>
<td>90%</td>
</tr>
<tr>
<td>HDPE</td>
<td>Separate</td>
<td>1.50</td>
<td>15%</td>
<td>90%</td>
</tr>
<tr>
<td>PET</td>
<td>Separate</td>
<td>1.50</td>
<td>15%</td>
<td>90%</td>
</tr>
<tr>
<td>PP</td>
<td>Separate</td>
<td>1.50</td>
<td>15%</td>
<td>90%</td>
</tr>
<tr>
<td>PS</td>
<td>NO</td>
<td>0.00</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>PVC</td>
<td>NO</td>
<td>0.00</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Others</td>
<td>NO</td>
<td>0.00</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Mixed</td>
<td>NO</td>
<td>0.00</td>
<td>100%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Finally, the plastic wasting sorting rates assume, in the selected settings, the values illustrated in Table 7. The high sorting rates are taken at different values depending on the collection system, in order to reach similar values to the actual collection system for separated fractions (for PET bottles and Aluminium cans) and mixed recyclables for which the collection rate is higher than 50%, as it is for paper and glass (Mattsson et al. 2009).

Table 7. Plastic Sorting Rates in the different possible settings. In between brackets are listed the scenarios in which a certain particular setting is used.

<table>
<thead>
<tr>
<th>Plastic Packaging</th>
<th>Mixed Collection – Low Sorting Rates (1)</th>
<th>Separate Collection – High Sorting Rates (2,4)</th>
<th>Mixed Collection – High Sorting Rates (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
</tr>
<tr>
<td>LDPE</td>
<td>20%</td>
<td>90%</td>
<td>70%</td>
</tr>
<tr>
<td>HDPE</td>
<td>20%</td>
<td>90%</td>
<td>70%</td>
</tr>
<tr>
<td>PET</td>
<td>20%</td>
<td>90%</td>
<td>70%</td>
</tr>
<tr>
<td>PP</td>
<td>20%</td>
<td>90%</td>
<td>70%</td>
</tr>
<tr>
<td>PS</td>
<td>20%</td>
<td>0%</td>
<td>70%</td>
</tr>
<tr>
<td>PVC</td>
<td>20%</td>
<td>0%</td>
<td>70%</td>
</tr>
<tr>
<td>Others</td>
<td>20%</td>
<td>0%</td>
<td>70%</td>
</tr>
<tr>
<td>Mixed</td>
<td>20%</td>
<td>0%</td>
<td>70%</td>
</tr>
</tbody>
</table>

From this data, following the indications given in detail in the next chapter on the material inputs of the modelling, all the selected scenarios can be derived. In Figure 10 and Figure 11 the inputs regarding waste generation and sorting are presented graphically.
Figure 10 - Per-Capita Plastic Waste Generation in the selected scenarios, divided by polymer. In between brackets are listed the scenarios in which a certain particular setting is used.

Figure 11 – Sorting Rates for Plastic waste in the selected scenarios. In between brackets are listed the scenarios in which a certain particular setting is used.
Modelling

After having defined the methodology, analysed the waste handling system and having discussed its possible evolutions in the 4 selected scenarios in the previous chapters, the evaluation tool, i.e. the model, can be built using these intermediate results of the study, taking into account inputs, outputs and evaluation criteria.

Structure of the Model

The model is composed by two sub-models, which represent the different waste handling operations. For plastic waste, the main handling options are, as previously discussed, incineration and recycling. Hence the first sub-model focuses on incineration of all the waste fractions, while the second sub-model simulates the recycling of plastic waste. The functional unit for the modelling is the single household. This choice was driven by the nature of the inputs (mainly waste generations) taken into account during the study. Almost all of them are proportional to the number of households living within the chosen system boundaries. At the same time, this allows to derive easily the results even for the whole County of Stockholm, multiplying the individual outputs for the number of inhabitants in the area.

Sub-Model 1: Mixed Household Waste Incineration

Following the concerns of the stakeholders managing the mixed household waste (incinerators’ owners and municipalities), the most interesting outcomes are the check on the combustibility and the calculation of the energy generated burning plastics in the incinerators. To the burning of plastics is connected another result, i.e. the plastic to be replaced in the production system using virgin raw materials, to which the production system and the regional governments should be interested. In Figure 12, the conceptual model of the sub-model regarding incineration of mixed household waste is illustrated.

![Conceptual model of SUB-MODEL 1: Incineration of Mixed household waste. Even though all the fractions are contributing to the overall waste composition that is influencing its combustibility (through the Heating Value HV, the Moisture Content M, the Ash Content A and the Combustible Fraction CF), only the energy generated by the combustion of plastic waste is accounted in the model.](image)
Material Inputs

The waste streams that are entering this first sub-model are:
- The mixed household waste;
- The plastic waste sorted for recycling.

In the modelling these two streams, being the single household the functional unit, are quantified from two main groups of inputs, which are:
- The per-capita waste generation on a dry base for each waste fraction \( W_{Gd} \);
- The per-capita waste sorting on a dry base for recycling for each waste fraction \( W_{Sd} \).

These groups of inputs are varied in respect to a base case, which tries to represent the operative conditions of the incinerators in the County of Stockholm for the year 2010 (good overall availability of data). Starting from the base case \( \bar{B} \), the per-capita waste generation on a dry base \( W_{Gd} \) can be varied for each \( i \)th waste fraction, indicating a per cent increase or decrease \( \frac{\text{var}}{100} \).

\[
W_{Gd_i} = \bar{B} \cdot \left(1 + \frac{\text{var}_i}{100}\right) \quad (1)
\]

On the contrary the per-capita waste sorting for recycling on a dry base \( W_{Sd} \) of a certain waste fraction is expressed as percentage \( \frac{\text{reci}}{100} \) of the per-capita waste generation \( W_{Gd_i} \), to be consistent with the common way to express the recycling performances of a system.

\[
W_{Sd_i} = \frac{\text{reci}_i}{100} \cdot W_{Gd_i} \quad (2)
\]

In the same way, the percentage of recycling can be varied from the base case to represent several possible future conditions.

Outputs

Analysing the conceptual model, the outputs from the first sub-model, considering all the fractions composing the mixed waste, are the characteristics of the mixed waste (average heating value HV, moisture content M, combustible fraction CF and ash content A), useful to investigate the combustibility of the waste.

While taking into account just the plastic fraction in the mixed waste, the outputs are:
- The energy (electricity and the heat) generated incinerating this fraction, influenced by the efficiency of electricity and heat production from incineration;
- The amount of plastics to be replaced in the production system after the energy recovery of the wasted ones.
Calculations

Characteristics of the mixed waste

The evaluation of the characteristics of the mixed waste (heating value \(HV\), moisture level \(M\), combustible fraction \(CF\), ash content \(A\)) can be easily made knowing the composition of the waste incinerated (see Figure 12), applying the method known as compositional analysis (Worrell & Vesilind 2012). Starting from the waste generation \((WGd)\) and sorting \((WSd)\) of each \(i^{th}\) waste fraction, the composition of the waste can be determined calculating the amount of waste (on a dry basis) that is actually incinerated \((WtoEd)\) for each waste fraction:

\[
WtoEd_i = WGd_i - WSd_i
\]  

(3)

The combustible fraction, the moisture content and the ash content are known on a wet basis, hence the amounts of waste to be incinerated have to be converted before to be consistent with the available data, using the moisture levels \((M)\).

\[
WtoE_i = \frac{WtoEd_i}{1 - M_i}
\]  

(4)

Finally the average characteristics of the considered waste can be calculated by weighted averages starting from the individual parameters of each waste category:

\[
CF_{AVG\ WtoE} = \frac{\sum_i WtoE_i \cdot CF_i}{\sum_i WtoE_i}
\]  

(5)

\[
M_{AVG\ WtoE} = \frac{\sum_i WtoE_i \cdot M_i}{\sum_i WtoE_i}
\]  

(6)

\[
A_{AVG\ WtoE} = \frac{\sum_i WtoE_i \cdot A_i}{\sum_i WtoE_i}
\]  

(7)

The average heating value of the waste \((HV_{AVG\ WtoEd})\) is influenced as well by the waste composition. However the heating values, differently from the other waste characteristics, are known on a dry base. Therefore, using always the compositional analysis, the average heating value can be computed as follows:

\[
HV_{AVG\ WtoEd} = \frac{\sum_i WtoEd_i \cdot HV_i}{\sum_i WtoEd_i}
\]  

(8)

This is the heating value on a dry base. However in the incineration facilities it can be handier to consider the heating value on a wet base, since this depends also on the moisture level. Therefore,
using the moisture level just computed with equation 6, the heating value on a wet base can be calculated:

\[
HV_{AVG\,WtoE} = HV_{AVG\,WtoEd} \cdot (1 - M_{AVG\,WtoE})
\] (9)

Electricity and Heat produced during Incineration

The electricity (\(EL_{fromW}\)) and heat (\(H_{fromW}\)) generation from an \(i^{th}\) plastic waste fraction are obtained multiplying the energy content of the correspondent waste fraction and the efficiency of the related conversion (\(\eta_{el\,WtoE}, \eta_{heat\,WtoE}\)). The energy content (\(EC\)) is given by the product of the dry amount of waste and the related heating value (\(HV\)).

\[
EC_{i} = W_{toEd_{i}} \cdot HV_{i}
\] (10)

\[
EL_{fromW1_{i}} = EC_{i} \cdot \eta_{el\,WtoE}
\] (11)

\[
H_{fromW1_{i}} = EC_{i} \cdot \eta_{heat\,WtoE}
\] (12)

Amount of plastic to be replaced in the production system

The amount of plastic to be produced again (\(PP_{fromVRM}\)) corresponds to the amount of plastic not sorted and then incinerated.

\[
PP_{fromVRM1_{i}} = W_{toEd_{i}}
\] (13)

This derivation holds if the production of plastic is constant in the year after the one modelled. In this case the plastic burnt will have to be replaced with virgin raw materials since the possibility of recycling has been precluded by the wrong sorting done by the households.

Sub-Model 2: Recycling of sorted Plastic Waste

Proceeding with the second sub-model, which is simulating the plastic recycling process, the desired outputs regard the energy to be used during the reprocessing and the actual material recovery. The aim of the recycling process is to extract the highest amount of secondary raw materials (with a reasonably low energy consumption) to be used again in the production system. The literature review highlights the importance of the actual use of the secondary raw materials to substitute the virgin ones (fossil fuels, mainly oil and natural gas) in the production of new plastic products (Finnveden et al. 2005). For this reason, in this modelling, just the secondary raw materials actually used for this purpose, equivalently to the virgin ones (to know how much virgin raw materials are saved) are considered to have a positive effect on the material balance.
However, instead of considering the amount of plastic effectively recycled, the plastic needed to replace the recyclables lost during the recycling process, or not used to replace virgin plastics, is accounted. This amount of plastic to be replaced can be easily added to the plastic lost during the incineration of the mixed household waste to know how much new plastic is needed from virgin raw materials to satisfy the needs of the production system. Considering instead the residuals of the recycling process, their contribution is accounted in terms of energy generated by means of incineration. In Figure 13, the conceptual model of the sub-model regarding recycling of sorted plastic waste is shown.

Figure 13 – Conceptual model of SUB-MODEL 2: Recycling of Sorted Plastic Waste.

**Inputs**
The only waste stream that is interesting for the second sub-model is the one related to the plastic waste collected for recycling. The way in which is expressed its variation has already been discussed for the first sub-model.

**Outputs**
The outputs for the sub-model related with recycling are:
- The energy use for recycling;
- The energy (electricity and heat) generated incinerating the residuals;
- The amount of plastics to be replaced in the production system because of material losses during the recycling process or because of missed substitution of virgin raw materials for plastic production.

**System Parameters**
The parameters that are influencing the behaviour of the model this time are:
- The electricity consumption during the recycling operations per mass of plastic collected ($E_{L_{f orREC}} pmp$);
- The material loss coefficient ($MLC$);
The virgin plastic substitution coefficient ($V_{PSC}$);
Efficiency of electricity and heat production from incineration ($E_{L from W2}$ and $H_{from W2}$).

The electricity consumptions for recycling and the material loss coefficients summarise in aggregated terms respectively the electricity use and the material efficiency of all the parts of the recycling process, considering all the separation steps, the shredding, the cleaning and the extrusion of pellets to be used in the production system. In order to be able to feed the model with likely values regarding the electricity consumptions and the material loss coefficients, a literature review of the recycling process was carried out and another model has been built to reproduce the recycling process itself to get eventually the desired information. In Appendix III - Model for Recycling Process, the model is shown and the values inserted in the main modelling are justified. The virgin plastic substitution coefficients are the most critical terms because of the problems in evaluating them (mainly for lack of data). The effects of this uncertainty are evaluated by means of uncertainty analysis.

Calculations

Total Electricity Consumption of the Recycling Phase
Knowing the electricity consumption ($E_{L for REC\ pmp}$) per mass of plastic collected for the recycling process of each plastic fraction and the amount of plastic collected for each plastic fraction, the calculation of the energy consumption related to a certain plastic fraction ($E_{L for REC}$) is straightforward:

$$E_{L for REC_i} = WSD_i \cdot E_{L for REC\ pmp_i}$$  \hspace{1cm} (14)

Summing up these values for all the plastic fractions, the total electricity consumption in the recycling process can be evaluated.

$$E_{L for REC} = \sum_i E_{L for REC_i}$$  \hspace{1cm} (15)

For further comparisons among the overall recycling processes, this value is normalised to the amount of plastic collected for recycling:

$$E_{L for REC\ pmp} = \frac{E_{L for REC}}{WS}$$  \hspace{1cm} (16)

Electricity and Heat generated incinerating the residuals
The electricity and the heat generated depend on the amount of residuals ($RR$) sent to energy recovery and on the efficiencies in energy generation of the waste-to-energy facilities. The amount of residuals for each plastic fraction depends on the material loss coefficient ($MLC$) during the
recycling process. The machines used for the separation of the different plastic fractions (usually collected together) are not perfect and part of the material is wrongly sorted and removed from the stream that arrives at the end of the recycling process. A similar phenomenon happens during the washing of the plastics. (Shonfield 2008)

\[ RR_i = MLC_i \cdot WS_i \]  
(17)

Wanting to determine the amounts of energy generated from the residuals (\( ELfromW2 \) and \( HfromW2 \)), the calculations are similar to the ones used in the first sub-model. The energy content of the plastic residuals (ECR) has to be multiplied for the efficiencies of the conversion to obtain the electricity and the heat generated.

\[ ECR_i = RR_i \cdot HV_i \]  
(18)

\[ ELfromW2_i = ECR_i \cdot \eta_{el\ WtoE} \]  
(19)

\[ HfromW2_i = ECR_i \cdot \eta_{heat\ WtoE} \]  
(20)

### Amount of plastic to be replaced

The amount of plastic to be produced again (\( PP\ fromVRM \)) corresponds to the sum of the amounts of plastic lost during the recycling process (\( RR \)) or not actually replacing virgin raw materials in the plastic production (\( PnotR\ forVPS \)).

\[ PP\ fromVRM2_i = RR_i + PnotR\ forVPS_i \]  
(21)

The last term in this last equation depends on the virgin plastic substitution coefficient and on the plastic effectively recycled (PR):  

\[ PR_i = (1 - MLC_i) \cdot WS_i \]  
(22)

\[ PnotR\ forVPS_i = (1 - VPSC_i) \cdot PR_i \]  
(23)

Again, to ease comparisons, these values can be normalised to the overall amounts of plastic actually collected for recycling, to obtain the percentage of virgin plastics substituted (\( VPS\% \)), of plastics recycled but not used to substitute virgin plastics (\( PnotR\ forVPS\% \)) and the material sent to energy recovery (\( RR\% \)).

\[ VPS\% = \frac{PR - PnotR\ forVPS}{WS} \]  
(24)
\[ P_{not \text{R for VPS}}\% = \frac{P_{not \text{R for VPS}}}{WS} \]  

\[ RR\% = \frac{RR}{WS} \]  

Assumptions, Simplifications and Exclusions

Some elements and processes have been simplified or cut-off from the system boundaries in order to ease the modelling and the evaluation of the scenarios. The choices done in the modelling are grouped in categories, listed and justified in the following sub-chapters.

Waste Characteristics

Here the simplifications are related mainly to the fractions of plastic waste. In fact equal moisture, ash content and combustible fraction have been assumed for all the fractions, even though for sure the ash content of PVC is higher for the high mineral content of the polymer (PlasticsEurope 2008). Moreover the waste sorted is assumed to be clean and moisture free \((WS_d = WS)\). This might not be true and the transportation needed for recyclables could be underestimated.

The last assumption here is that the different plastic fractions are sorted for recycling all with the same rate of diversion, regardless for the plastic type. This might not be the case since the household could perceive different plastic compositions in different ways and sort the materials more or less efficiently. However no data were found regarding the detailed composition of the plastic fractions collected for recycling.

Waste Collection

Considering the collection of the different waste fractions, the related energy use has been neglected since this is anyway a part of the overall procedure to be accomplished in the waste handling, independently from the waste sorting. However some studies shows how the collection of recyclables is usually more energy consuming, with a higher impact in the transportation category (Naturvårdsverket 2009).

Moreover, even if the collection system is not modelled, its effects on the other processes that are modelled cannot be ignored. The collection system might influence the rates of waste sorting (Naturvårdsverket 2009) and the waste treatment process, above all the recycling. In fact the way in which the collection is carried out affects the separation steps needed in the recycling facilities. For instance a separate collection for just one waste fraction would require fewer efforts for the separation and higher quality of the recycled fraction, as it happens for the recycling of PET bottles.
under the deposit system for beverages (Returpack 2012). Therefore the effects of a changed collection pattern are included changing the system parameters of the sub-model for the recycling phase.

**Waste Handling after Collection**

The sorted waste is usually baled in dedicated facilities after collection and before the shipment. This process is not considered in the modelling because of its low energy consumption (Lewis 2012) and because it is not affecting any other characteristic of the waste fractions.

**Incineration Process**

In the model for the incineration process, the efficiencies of the incinerators in electricity and heat production are not influenced by the average heating value of waste. If the average heating value of waste is lower than the design value no explanation is needed since the heating value is increased using oil to support the combustion. If the average heating value of waste is higher than the design value, the characteristics of the steam generated are assumed to be anyway constant.

**Waste Transportation**

The waste transportation impacts have been neglected, using the results of a study that shows how this impact is usually negligible (Finnveden et al. 2005).

**Recycling Phase**

For the plastic recycling just mechanical recycling has been considered. This is because at the moment the feedstock recycling is still at very low values (Mudgal et al. 2011). However the model could be easily adapted to include this kind of treatment, using other data regarding energy use and material efficiencies. Moreover no forms of energy other than electricity have been considered to be used during recycling. However the electricity consumption has been overestimated starting from the evaluations in the dedicated model on the actual recycling processes (see Appendix III - Model for Recycling Process).

**Use of Secondary Raw Materials**

The secondary raw materials that are not used to substitute plastic from virgin raw materials have been excluded from the system boundaries. Therefore the mass balance in the recycling process is not respected, but the exclusion is justified by some reviewed studies, which highlight the importance of replacing virgin plastics to have an environmental gain when recycling (Finnveden et al. 2005).
Emissions to air, water and land

The following arguments are also related to water consumption and treatment of ashes from incineration. In the described model these elements, together with the emissions to air, water and land, have been excluded, although generally not negligible. This is because, above all for the incineration, these elements are not considered influenceable by the major inputs in this modelling, which are waste generation and sorting for recycling. In fact the incinerators are assumed to operate anyway in the next 20 years. The amount of waste to be imported might change, but the incinerators will still require treatment of ashes and will still have emissions to the environment. These processes could change because of technology development, but not directly because of changes in the overall generation or in the treatment of sorted plastic waste. And again these changes in the processes would not strongly affect the results, because of the chosen evaluation method, based on fossil fuels consumption.

Aggregated Evaluations for Scenarios Comparison

At this point the results of the two sub-models can be combined in order to get the overall picture about the fate of the plastic waste and the outcomes of the different scenarios using the defined evaluation criteria. As announced in the methodology section, the results in terms of energy available from the balance of generation in the incinerators and use in the recycling plants can be combined with the amounts of plastic to be replaced in the production system through the constant fossil fuels use hypothesis, and the conversion of the fossil fuels saved or depleted in energy (see Figure 2). However, before applying the constant fossil fuels use hypothesis, the amounts of plastic to be replaced have to be converted in fossil fuels equivalents.

Electricity Available

Electricity is generated from the local incineration of plastics in mixed waste and from the incineration of the recycling process residuals. Summing up these two, the total electricity generation from plastic waste (ELfromW) can be computed.

\[
EL_{fromW1} = \sum EL_{fromW1i} 
\]

(27)

\[
EL_{fromW2} = \sum EL_{fromW2i} 
\]

(28)

\[
EL_{fromW} = EL_{fromW1} + EL_{fromW2} 
\]

(29)

However, part of the electricity generated is used in the recycling process. Therefore the electricity available (EA) at the end is lower than the total electricity generation.
\[ EA = EL_{fromW} - EL_{forREC} \] (30)

**Heat Available**

The heat generated \((H_{fromW})\) can be computed in similar way to the electricity generated. The contribution from the local incineration and from the incineration of plastic residuals can be calculated as follows.

\[ H_{fromW1} = \sum H_{fromW1_{i}} \] (31)

\[ H_{fromW2} = \sum H_{fromW2_{i}} \] (32)

\[ H_{fromW} = H_{fromW1} + H_{fromW2} \] (33)

In this case the heat generated corresponds to the heat available \((HA)\), since the recycling processes are assumed to use just electricity

\[ HA = H_{fromW} \] (34)

**Fossil Fuels Conversions of amounts of plastics to be replaced with Virgin Raw Materials**

The conversion is done using the data available in the eco-profiles drawn up by Plastics Europe regarding the production of the different plastic polymers (PlasticsEurope 2008) and specifically taking into account the amount fossil fuels used in the production \((FFPP_{fromVRM pmp, feedstock plus energy per unit mass of a certain plastic polymer})\). Multiplying this value times the mass of plastic to be replaced, the fossil fuels to replace a certain plastic fraction \((FFPP_{fromVRM X_{i}})\) can be computed (where \(X\) stays for 1 or 2, referring to the sub-model for incineration or for recycling):

\[ FF_{fromVRM X_{i}} = FF_{fromVRM pmp_{i}} \cdot PP_{fromVRM X_{i}} \] (35)

Summing all the amounts of fossil fuels to replace each plastic fraction, the overall amount of fossil fuels needed to replace plastic \((FFPP)\) is obtained:

\[ FFPP = \sum FF_{fromVRM1_{i}} + \sum FF_{fromVRM2_{i}} \] (36)

The fossil fuels used in the production of plastics are mainly natural gas and crude oil (PlasticsEurope 2008). For this conversion the amount of fossil fuels is assumed to represent just crude oil. From an energetic point of view, since the heating value of natural gas is higher than the
one of crude oil (World Energy Council 2012), this involves an underestimation of the energy available in the saved fossil fuels.

Constant Fossil Fuels Use Hypothesis and Scenarios Comparison

The fossil fuels use for plastic replacement, computable for the each scenario, compared with the base case, leads in a saving or in an additional depletion of fossil fuels in respect to the current use. The constant fossil fuels use hypothesis at this point requires to convert in energy equivalents these fossil fuels use variation, assuming the use of these fossil fuels in combined heat and power plants (CHPs). The derivation is explained in the following paragraphs.

From each \(j^{th}\) scenario, accounting for the last treatments on the sub-models’ outputs, three main values are known:
- Fossil Fuels use for plastic replacement;
- Electricity available from plastic waste handling;
- Heat available from plastic waste handling.

In respect to the base case, the variation of these values can be evaluated:

\[
FFPP_{Var} = FFPP_j - FFPP_{BC}
\]

\[
EA_{Var} = EA_j - EA_{BC}
\]

\[
HA_{Var} = HA_j - HA_{BC}
\]

At this point the \(FFPP_{Var}\) can be converted in electricity and heat \((EA_{FFPP_{Var}}\) and \(HA_{FFPP_{Var}}\)), using the efficiencies of a CHP fossil fuels plant for the energy conversions \((\eta_{elCHP}, \eta_{heatCHP})\).

\[
EA_{FFPP_{Var}} = -FFPP_{Var} \cdot HV_{oil} \cdot \eta_{elCHP}
\]

\[
HA_{FFPP_{Var}} = -FFPP_{Var} \cdot HV_{oil} \cdot \eta_{heatCHP}
\]

Finally the variation in electricity and heat available corrected with the constant fossil fuels use hypothesis can be evaluated.

\[
EA_{Var}' = EA_{Var} + EA_{FFPP_{Var}}
\]

\[
HA_{Var}' = HA_{Var} + HA_{FFPP_{Var}}
\]
Model Testing

Testing the model means first of all trying to run it and see if the results that the model itself is providing find correspondence in the real world. After the comparison of the first results of the model with actual data, sensitivity and uncertainty analyses are carried out in order to understand which parameters should be treated more carefully to enhance the reliability of the results.

Calibration and Validation

As for the model description, also the model validation is stepwise.

Sub-Model 1

There are some data available from the incinerator of Stockholm (Högdalenverket) that can be used in the attempt of validating the average waste characteristics modelled, which are the electricity and heat produced from the furnaces that are burning mainly household waste, partially mixed with industrial waste. In Table 8 the data are listed.

Table 8. Data on operations of Högdalenverket for the year 2010 regarding the furnaces burning mainly household waste (Fortum AB 2011)

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Year 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heat Produced</strong></td>
<td>(GWh)</td>
<td>1041</td>
</tr>
<tr>
<td><strong>Electricity Produced</strong></td>
<td>(GWh)</td>
<td>145</td>
</tr>
<tr>
<td><strong>HH Waste</strong></td>
<td>(tons)</td>
<td>403199</td>
</tr>
<tr>
<td><strong>Industrial Waste</strong></td>
<td>(tons)</td>
<td>100445</td>
</tr>
<tr>
<td><strong>Oil to Support the Combustion</strong></td>
<td>(m³)</td>
<td>1332</td>
</tr>
</tbody>
</table>

The waste composition modelled in the base case is the one for the year 2011, while unluckily there are still no data available for that year regarding energy production. However these data can still be used as a test, trying to evaluate the efficiencies of the incinerator in electricity and heat production using the evaluated average heating value and the average moisture content (needed to compute the amount of dry waste). In Table 9 the results for the Base Case in terms of waste characteristics are presented.

Table 9. Characteristics of the mixed household waste to incineration in the Base Case

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Year 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heating Value, dry base</strong></td>
<td>(MJ/kg)</td>
<td>11.24</td>
</tr>
<tr>
<td><strong>Moisture Level</strong></td>
<td>(-)</td>
<td>44.6%</td>
</tr>
</tbody>
</table>
To be able to compare the data on the energy production with the ones outputted by the model, also the industrial waste ($W_{toEd_{ind}}$) needs to be considered together with the household waste ($W_{toEd_{hh}}$) and since no studies have been done on purpose for this project, the average upper heating value of dry industrial waste is taken from literature (20 MJ/kg, (Process Combustion Corporation 2012)). Similarly the moisture level of industrial waste is set at 10% (Process Combustion Corporation 2012).

The efficiencies are then computed as follows:

$$\eta_{heat\ WtoE} = \frac{Heat\ Produced}{W_{toEd_{hh}} \cdot HV_{AVG\ WtoEd_{hh}} + W_{toEd_{ind}} \cdot HV_{IND}} \quad (44)$$

$$\eta_{el\ WtoE} = \frac{Electricity\ Produced}{W_{toEd_{hh}} \cdot HV_{AVG\ WtoEd_{hh}} + W_{toEd_{ind}} \cdot HV_{IND}} \quad (45)$$

In Table 10 the starting data and efficiencies computed are shown.

Table 10. Results of calculations made on Högdalenverket using the outputs of the model for the Base Case

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Year 2010 - 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency in Heat Generation</td>
<td>86%</td>
</tr>
<tr>
<td>Efficiency in Electricity Generation</td>
<td>12%</td>
</tr>
<tr>
<td>Overall Efficiency</td>
<td>98%</td>
</tr>
</tbody>
</table>

The overall efficiency derived seems to be too high, even though it is not very far from likely data (overall efficiency of 90-95%, (Profu AB 2004)). However, because of the number of parameters included and of level of uncertainty of the most part of them it would not be very meaningful to attempt a calibration.
Sub-Model 2
No data have been found to validate this part of the model. However the effects of the variation of the parameters related with this part of the model (electricity use for recycling, material loss coefficients, virgin plastic substitution coefficients) are studied in the sensitivity analysis.

Sensitivity Analysis
The sensitivity analysis is carried out for the whole model at once since there are common parameters that are influencing both the sub-models. The influence of these parameters is examined on the three main outputs of the modelling that are then used in the aggregated evaluation, which are:

- Fossil fuels use in plastic production (FFPP), computed following equation 36;
- Electricity available (EA), computed following equation 30;
- Heat available (HA), computed following equation 34.

The only part of the results that is not examined is the one related to the waste characteristics. In this case, being the parameters examined (heating value, moisture level, combustible fraction and ash content) just obtained by weighted averages, there is no need to carry out a complete sensitivity analysis to understand the effects of parameters variation on the outputs.

Fossil fuels use in plastic production
The parameters that are influencing this output are:

- Plastic waste generation ($W_{G_{Plastic}}$);
- Plastic waste sorting ($W_{S_{Plastic}}$);
- Material losses in the recycling process ($MLC$);
- Virgin plastic substitution coefficients ($VPSC$);
- Fossil fuels for plastic production from virgin raw materials ($FFPP_{fromVRM}$).

These parameters can have different values for each plastic waste fraction. However, in this sensitivity analysis, they are varied at the same time for all the plastic waste fractions. The results of the sensitivity analysis are shown in Figure 14.
Figure 14 – Sensitivity Analysis regarding the fossil fuels use for plastic production after the whole plastic waste treatment. The trend lines show the % change in the evaluated result related to a % change of the considered parameters.

It is important to point out that these results depend on the chosen starting point. Wanting to be able to vary all the parameters in the range +/-100%, the values already expressed in percentages ($PWS, MLC, VPSC$) have been set at 50%. However, with another choice of the base case, the importance of these parameters would have changed. For example, if the evaluation had started with zero plastic waste sorting, the changes in material loss coefficient or in virgin plastic substitution coefficient would not have affected the results, since no plastic would have entered the recycling system. In any case, bearing in mind these limits, this sensitivity analysis gives a sense of the importance of the different parameters.

Moreover, for some of the parameters (e.g. fossil fuels for production of a unit of mass of plastics), the big range of variation is not representing the actual range of variation (e.g. 1 kg of plastic cannot be obtained with less than 1 kg of fossil fuels), but again the sensitivity analysis helps to give relevance to the parameters that have to be judged more carefully to have reliable results.

Summarising, it is worthy to note how the waste sorting and the quality of the recycling process (in terms of material losses and virgin plastics substitution) have the same not negligible impact on the system. The plastic waste sorting variation has the same effects of the virgin plastic substitution variation, putting them on the same level of relevance (even though in the waste management policies the waste sorting is the only concerns, without any constraint on the use of the secondary...
raw materials). Nonetheless, the most important parameter is the plastic waste generation and just a “perfect” reprocessing (100% sorting, zero material loss, complete virgin plastic substitution), which is definitely unlikely, can yield to similar results.

Electricity Available
Looking at the precedents of equation 30, the parameters that are influencing the electricity available (EA) at the end of the incineration processes (on the household waste and on the plastic residuals) and of the recycling process are:

- Plastic waste generation ($W_{G_{Plastic}}$);
- Plastic waste sorting ($W_{S_{Plastic}}$);
- Incinerators’ Efficiency ($\eta_{incinerators}$);
- Heating value of plastics (HV of Plastics);
- Material losses in the recycling process ($MLC$);
- Electricity used in the recycling process ($EL_{forREC}$).

Again the values are varied one by one but together for all the plastic waste fractions. In Figure 15 the results of the sensitivity analysis are presented.

![Sensitivity Analysis for Electricity Available](image)

Figure 15 - Sensitivity Analysis regarding the electricity available after the whole plastic waste treatment. The trend lines show the % change in the evaluated result related to a % change of the considered parameters.

Similarly to the fossil fuels use for plastic replacement, the electricity available, being the material input of the modelling, is exactly proportional to the plastic waste generation. However, in this
case, the efficiency of the incinerators and the heating values of plastics play a more important role. When they reach their minimum values, the electricity available can even reach negative values. This is because this setting would imply a zeroing of the energy generation, despite the electricity for recycling would still be needed. The electricity for recycling becomes a parameter with a comparable level of relevance when considering that in the real world it can vary in a range higher than the one considered here. From the previous figure it is still interesting to note how the growth of the material loss coefficient has a positive effect on the electricity available, increasing the amount of plastic available for incineration.

**Heat Available**

Considering the heat available (HA), again both the incineration and the recycling process are relevant. However this time just the material loss coefficients play a role from the recycling process, having considered just electricity as energy needed during the recycling process. Therefore the parameters that are influencing the heat available are:

- Plastic waste generation ($WG_{Plastic}$);
- Plastic waste sorting ($WS_{Plastic}$);
- Incinerators' Efficiency ($\eta_{incinerators}$);
- Heating value of plastics (HV of Plastics);
- Material losses in the recycling process ($MLC$).

In Figure 16 the results of the sensitivity analysis on the heat available are shown.

![Sensitivity Analysis for Heat Available](image)

**Figure 16** - Sensitivity Analysis regarding the heat available after the whole plastic waste treatment. The trend lines show the % change in the evaluated result related to a % change of the considered parameters.
Here the situation is quite similar to the one for the electricity available, but not complicated by any sink of energy in the recycling process. The efficiency of the incinerators is the most important parameter, together with the plastic waste generation, considering the actual range of variation of all the parameters (the heating value of plastics cannot vary in the considered range).

**Uncertainty Analysis**

Caring more about judging the potential of the model than about the particular results of this study, just one group of parameters has been considered for this uncertainty analysis, i.e. the virgin plastic substitution coefficients. This is because these coefficients could be uncertain even in a real setting, depending not just on the quality of the secondary raw materials but also on the global market. In fact, even the availability of good quality raw materials, potentially usable for the same applications of the virgin raw materials, do not guarantee the actual substitution of these virgin raw materials. This could be for different reasons, from the price of virgin and secondary raw materials for example to the adjustment of production processes in order to be able to use the secondary raw materials. Other parameters, like the material loss coefficients and the electricity use for recycling, are highly uncertain in this study, but not in general, since almost all of them are measurable with reliable experiments. Of course they are anyway uncertain, since there is no perfect measure, but a higher availability of data, above all from the recycling plants, is needed to proceed with meaningful considerations.

At this point it is hard to talk about uncertainty analysis, since just one group of parameters is considered. However, this analysis can be used as first check to know if further uncertainty analysis is needed or not. In fact, if just the uncertainty of the virgin plastic substitution coefficients leads to an overlap of the results, it means that the model cannot produce usable results for the examined case and further studies are not necessary. Otherwise, it means that additional studies could be useful to test more deeply the model.

After this introduction, wanting to define the range of uncertainty of the results, the uncertain parameters have to be varied in order to find the “high” and “low” values of the outputs. Useful information about how to vary the parameters can be found in the sensitivity analysis. In fact, from that component of the model testing it is possible to know if a certain parameter increases or decreases a certain output. In the case of the virgin plastic substitution coefficients, they are influencing only the fossil fuels use and in particular, an increase in the virgin plastic substitution coefficients yields in a decrease of the fossil fuels use, in the way Figure 14 is showing. At the end of the results section, the effects of this uncertainty are examined directly on the results.
Modelling Results

The model can now be fed with the scenarios selected previously. In this way the scenarios, which represent likely future setting of the plastic waste handling system, can be evaluated in the defined terms, passing through the combustibility of the mixed household waste, the energy obtained or needed by incinerating or recycling the plastic waste, the plastic to be replaced in the production system, and arriving at the aggregated output, which is the corrected energy available variation in respect to the base case, as mentioned in the methodology section and explained after the model structure description.

Sub-Model 1: Mixed Household Waste Incineration

As explained in the model description, the outcomes of the sub-model related to the mixed household waste incineration are:

- The waste characteristics to check the combustibility of waste;
- The electricity and the heat available from the incineration of the plastic contained in the mixed household waste;
- The amount of plastic to be replaced in the production system after the incineration process.

Waste Characteristics and Check on Combustibility

In Figure 17 and Figure 18 the average characteristics of the mixed waste (average heating value on a dry and wet base, moisture content, combustible fraction and ashes) sent to incineration are summarised.

![Average Heating Value of Household Waste partially mixed with Industrial Waste](image)

Figure 17 – Average heating value on a wet base of mixed household waste mixed with industrial waste as in the current setting. The numbers below the bars refer to the different scenarios evaluated, which are briefly explained in the legend of the figure.
Figure 18 – Moisture Level, Combustible Fraction and Ash Content of the mixed household waste, always mixed with industrial waste. The numbers below the bars refer to the different scenarios evaluated, which are briefly explained in the legend of the figure.

In the selected scenarios, none of them yield to waste characteristics that could lead to problems in the combustion. In fact in all the cases the moisture level, the combustible fraction and the ash content are within the prescribed limits to avoid the use of auxiliary fossil fuels, which could be useful to remind:

- Combustible fraction $CF < 25\%$;
- Moisture content $M > 50\%$;
- Ash content $A > 60\%$.

Even the average heating value on a wet basis is always around the design value (10 MJ/kg). The lower heating value is scored by the third scenario (9.5 MJ/kg), the one that considers high sorting rates for all the plastics. However this value is not very different from the Base Case heating value (9.7 MJ/kg).

**Electricity and Heat Available from Plastic in Mixed Household Waste Incineration**

In Figure 19 are presented the outputs of the first sub-model in terms of energy produced from the incineration of the plastic waste in the incineration plant for mixed household waste (that in this case could be Högdalenverket for example).
Figure 19 – Electricity and Heat generated in the incineration facilities from the combustion of plastic waste contained in the mixed household waste. The numbers below the bars refer to the different scenarios evaluated, which are briefly explained in the legend of the figure.

None of the scenarios considered, taking into account the heat generation, reaches a level higher of the Base Case. On the contrary, the decrease of heat generation can be substantial, becoming the half in Scenario 2 and one third in Scenario 3. Reminding the characterisation of the different scenarios, the results here are mainly influenced by the sorting rates for plastic waste, which eventually determine the amounts of plastics combusted in the incineration facility that burns household waste. In fact, the lowest heat generations are scored by Scenario 2, 3 and 4, which are the ones considering high sorting rates. The differences among these three scenarios are then caused by the type of collection. Scenario 3 considers a mixed collection and therefore all the plastic fractions are sorted for recycling independently on their composition, while Scenario 2 and 4 feature a separated collection for only a few polymers. Hence, although having very high sorting rates for those fractions, some of the polymers are not collected at all and they can help in maintaining high the amount of plastic incinerated.

The electricity generation has the same kind of trend in respect to the heat generation, proportional to the amount of plastic burnt, but, in comparison with the Base Case, the performances are almost always higher (just once slightly lower, in Scenario 3). This is because of the increased efficiency for electricity production considered in all the scenarios in respect to the Base Case.
Amount of Plastic to be replaced in the production system after incineration in mixed household waste

In Figure 20 the amounts of plastic to be replaced in the production system, because incinerated with the mixed household waste, are shown. These results are strictly related with the performances in heat and electricity generation illustrated in Figure 19. In fact, comparing Figure 19 and Figure 20, it is evident how the energy generation is proportional to the amount of plastic incinerated.

![Plastic to be replaced after plastic combustion in Mixed Household Waste](image)

Figure 20 – Amount of plastic to be replaced after incineration in the mixed household waste. The numbers below the bars refer to the different scenarios evaluated, which are briefly explained in the legend of the figure.

Sub-Model 2: Recycling of sorted plastic waste

Here the focus is on the outcomes (in terms of plastic to be replaced after the recycling process and of energy generated incinerating the residuals) and on the energy requirements of the recycling process, depending on the characteristics of material inputs (influenced by the organisation of the collection) and on the recycling process itself. In Figure 21 the amount of plastic collected for recycling in each scenario is shown in comparison with the Base Case.
Figure 21 – Amounts of plastic collected for recycling in the different scenarios. The numbers below the bars refer to these different scenarios, which are briefly explained in the legend of the figure.

This figure is helpful to understand the results that in the next paragraphs are expressed.

**Electricity use for recycling**

In Figure 22 the results for the electricity use of the recycling process are summarised graphically. The electricity used for the plastic recycling in the different scenarios depends first of all on the amount of plastic processed (see Figure 21). Therefore the highest electricity uses are scored by Scenario 2, 3 and 4, because of the high sorting rates at the collection step. However, if the amount of plastic collected for recycling was the only important parameter, the highest electricity use should be featured by Scenario 3 (for which just 8 kg of plastics are incinerated, and the other 19 kg are collected for recycling). This does not happen because of the differences in the recycling process. In fact, in Scenario 3, some of the plastics collected (PS, Others) are removed at once from the main stream and sent directly to energy recovery (see Table 6). Therefore, the electricity use connected to these fractions is lower than in the other cases, and the highest electricity use is performed by Scenario 2, in which all the plastics collected for recycling undergo the whole recycling process.

Figure 22 – Total electricity use for the recycling process in the different scenarios. The numbers below the bars refer to the different scenarios evaluated, which are briefly explained in the legend of the figure.
Electricity and heat generated incinerating the residuals of the recycling process

In Figure 23 the results regarding electricity and heat generated incinerating the residuals of the recycling process are presented. Here the results are influenced not only by the amounts of plastic collected for recycling, but also by the material loss coefficients in the recycling process. Scenario 1 and Scenario 3, because of the mixed collection of the recyclables, have higher material loss coefficients for all the polymers if compared with the recycling process for separated fractions. Therefore the amounts of plastic incinerated increase dramatically between Scenario 2 (which has low material loss coefficients because of the separated collection) and 3, even though the inputs are comparable (see Figure 21). This eventually yields to a heat generation that spans from 8 kWh/pers in the Base Case to the 56 kWh/pers in Scenario 3 and to an electricity generation that ranges from 1 to 15 kWh/pers for the same scenarios.

![Electricity and Heat Available from Incineration of Plastic Recycling Residuals](image)

**Figure 23** – Electricity and Heat available from the energy recovery of the amounts of plastics rejected by the recycling process. The numbers below the bars refer to the different scenarios evaluated, which are briefly explained in the legend of the figure.

Amounts of plastic to be replaced in the production system after Recycling

The results in this category, and shown in Figure 24 complete the picture introduced by the energy generate from the residuals (see Figure 23). If from one side substantial portions of plastics rejected by the recycling process increase the energy generation, on the other side this increases the amounts of plastic to be replaced in the production system. Therefore again Scenario 3 scores the highest result. The situation is even worsened by the virgin plastic substitution coefficients featured by the scenarios with the mixed plastic collection (1 and 3), which are lower than the ones for the recycling process for separated plastic waste (see Table 6). In opposition to these results,
remarkable is the performance of Scenario 2 and 4, which succeed in recovering efficiently roughly the 80% of the plastic collected for recycling. In fact, for Scenario 2, just 4 kg of the 17 kg collected for recycling have to be substituted with virgin raw materials at the end of the recycling process.

Figure 24 – Amounts of plastic to be replaced in the production system after the recycling process. These results are strongly influenced by the material loss coefficients and by the virgin plastic substitution coefficients of the different recycling process performed by the different scenarios. The numbers below the bars refer to the different scenarios evaluated, which are briefly explained in the legend of the figure.

**Aggregated Results**

Following the modelling description, the results have also been aggregated to get the overall picture of the performances of the different plastic waste generation and handling settings in terms of corrected variation in the energy balances in respect to the base case ($EA'_{var}$ and $HA'_{var}$). The different steps needed to arrive to the aggregated results are shown in the next paragraphs. The electricity and heat available from the incineration of both plastic in the mixed household waste and of plastic residuals are corrected by the energy surplus or deficit imposed by the constant fossil fuels use hypothesis (where the fossil fuels uses are related to the plastic replacement in the production system) and all the results of the 4 considered scenarios are compared with the Base Case, from which also the fossil fuels use assumed as constraints has been derived.

**Electricity and Heat Available**

The total electricity and heat available at the end of the plastic waste processing represent the sum of the energies generated in the incineration of plastic waste in the mixed household waste or of plastic waste residuals after the recycling process minus the energy necessary to power the
recycling process (assumed to be only electricity). In Figure 25 the total electricity available in the different scenarios is shown, while Figure 26 presents the heat available.

Figure 25 – Electricity available from incineration of plastic waste (of not sorted plastic waste or of plastic recycling residuals) reduced by the electricity use for recycling. The numbers below the bars refer to the different scenarios evaluated, which are briefly explained in the legend of the figure.

Figure 26 - Heat available from incineration of plastic waste (of not sorted plastic waste or of plastic recycling residuals). The numbers below the bars refer to the different scenarios evaluated, which are briefly explained in the legend of the figure.

The differences among the scenarios are less noticeable than considering only the energy generation from the mixed household waste or the one from plastic recycling residuals. This is because in general the high sorting rates shift the plastic waste towards the recycling process, where anyway not all the plastics are recovered effectively. The lowest energy generation is performed by Scenario 2. This is connected to the very good performances in recycling plastic waste, which left low amounts plastic to the incineration.
Fossil Fuels for Plastic Replacement

The conversion of the amounts of plastic to be replaced in production system is one of the steps needed for the generation of the aggregated results (explained in the methodology section). In Figure 27 the amounts of fossil fuels needed in the different scenarios are presented.

As for the energy generation, the high sorting rates shift also the responsibility of the plastic replacement towards the recycling process. In Scenario 1 it is possible to see the effects of the increased plastic waste generation in respect to the Base Case, coupled with similar plastic waste handling and similar sorting rates. The fossil fuels need increases almost proportionally to the plastic waste generation. Scenario 1 is also the only configuration, among the ones considered, which performs a higher fossil fuels use. The other configurations, even the one in Scenario 3, allow a fossil fuels saving in respect to the Base Case. However Scenario 3 shows the inefficiency of its recycling process, requiring the highest amount of fossil fuels to replace the plastics lost in the recycling process.

At this point, to produce the aggregated results, the constant fossil fuels use hypothesis is introduced. In Figure 28 the amounts of fossil fuels saved or depleted in comparison with the base Case are highlighted. These fossil fuels, if saved, can be used to generate additional energy in combined heat and power plants, while if depleted, are removed from the energy generation, resulting in a reduction of energy available.
Figure 28 – Saving (if negative) or depletion (if positive) of fossil fuels that can be used for energy generation in combined heat and power plants in respect to the base case. The numbers below the bars refer to the different scenarios evaluated, which are briefly explained in the legend of the figure.

Corrected Electricity and Heat Available Variation

Finally, taking into account the electricity and the heat available from incineration and the fossil fuels that can be used in energy generation, the corrected electricity and heat available variation ($EA_{var}'$ and $HA_{var}'$) can be obtained comparing the total energy available in each scenario with the Base Case. In Figure 29 the results are summarised.

Figure 29 – Corrected Electricity and Heat Available ($EA_{var}'$ and $HA_{var}'$) variations in comparison with the Base Case, after having applied the constant fossil fuels use hypothesis. The numbers below the bars refer to the different scenarios evaluated, which are briefly explained in the legend of the figure.
Introducing the constant fossil fuels use hypothesis the situation is almost completely reversed if compared with the energy generation from incineration. Scenario 2 totalises the best results both for electricity and heat generation among the scenarios considered, while considering only the energy generated from incineration of plastic waste in mixed household waste and of plastic recycling residuals. Scenario 2 performs the worst result. The second best result is achieved by Scenario 4. This implies that the separate collection for PE, PET and PP (assumed for Scenario 2 and 4), independently from the waste generation considered (at least for the considered scenarios), leads to better results than the mixed collection of plastic waste (assumed for Scenario 1 and 3).

Talking about Scenario 1, even though it has a doubled electricity generation from incineration respect to the Base Case, the constant fossil fuels hypothesis leads to a negative variation of corrected electricity available. Scenario 3 scores the worst result in terms of heat generation, while overcoming Scenario 1 regarding electricity available. This is because of the difference in energy generation in a combined heat and power plant for fossil fuels in respect to an incineration facility. In fact, in a combined heat and power plant powered with oil or natural gas, the efficiency in electricity generation is around the 50% (45% for heat), against the 25% for the incinerators (70% for heat). This implies, when applying the constant fossil fuels use hypothesis, on Scenario 1, a steeper reduction in electricity available than in heat available. This phenomenon is visible even in the other scenarios, for which the electricity balances are more helped than the heat balances by the fossil fuels combustion. The fact that the results are more clear in terms of electricity variations is not a drawback, since electricity is the most valuable form of energy.

**Uncertainty of Results**

Following the indications given in the sub-chapter related to the uncertainty analysis, the effects of the variation of the virgin plastic substitution coefficients on the results is explored. It is worthy to remind how only the uncertainty on the virgin plastic substitution coefficients has been addressed, needing more pieces of information to proceed with a complete uncertainty analysis. In Figure 30 Error! Reference source not found. and Figure 31 the effects of the variation of the virgin plastic substitution coefficients in a range +/-20% on the corrected variation of electricity and heat available are shown.
Figure 30 - Uncertainty on the Corrected Variation of Electricity Available considering only the uncertainty on the virgin plastic substitution coefficients. The numbers below the bars refer to the different scenarios evaluated, which are briefly explained in the legend of the figure.

Figure 31 - Uncertainty on the Corrected Variation of Heat Available considering only the uncertainty on the virgin plastic substitution coefficients. The numbers below the bars refer to the different scenarios evaluated, which are briefly explained in the legend of the figure.
Even though these uncertainties do not apply at these particular results, since the virgin plastic substitution coefficients are not the only uncertain input data in this use of the model, some general considerations can be drawn. The uncertainty on the virgin plastic substitution coefficients yields in a difference between highs and lows of 5-35 kWh/pers/year both in the values of electricity and heat, with higher differences when the system is relying more on recycling than on incineration. For the selected scenarios this uncertainty does not preclude the possibility to prefer a certain scenario to another one being Scenario 2, at least for the electricity available, the best option in the whole range of uncertainty. However this applies only for the variation in electricity available, while the situation is more cryptic for the heat generation, since, already without considering the uncertainty, the results are quite unclear.

The analysis is not complete, but it helps in understanding how reliable data must be provided in each sector to obtain trustful results. Otherwise almost nothing can be said in respect to the selected scenarios. For instance, hypothesising to know the range of variation of other parameters used for the evaluations in this study, the situation worsens rapidly. In Table 11 the parameters used for the example are listed with the related ranges of variation.

Table 11. Ranges of parameters variation for the extended evaluation of the extreme uncertainty of the results

<table>
<thead>
<tr>
<th>Variation for</th>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ELforREC</strong></td>
<td>-50%</td>
<td>200%</td>
</tr>
<tr>
<td><strong>VPSC</strong></td>
<td>20%</td>
<td>-20%</td>
</tr>
<tr>
<td><strong>FFPP</strong></td>
<td>-10%</td>
<td>10%</td>
</tr>
</tbody>
</table>

As it can be seen in Figure 32, these variations are enough to have the lowest corrected electricity available variation for Scenario 2 (that has been considered as the best one so far) below all the other Scenarios at the highest result.
Figure 32 - Uncertainty on the corrected electricity available variation considering possible uncertainties on the virgin plastic substitution coefficients, on the electricity use for recycling and on the fossil fuels needed to replace the plastics in the production system. The numbers below the bars refer to the different scenarios evaluated, which are briefly explained in the legend of the figure.
Discussion

The aim of the study was to investigate the performances of facilities that are taking part into the plastic waste handling in order to point out the combinations of plastic waste generation and handling, exemplified by four different scenarios, which lead to better or worse results. The ranking of the results has been made following the selected evaluation criteria, which are energy (electricity and heat) generation and fossil fuels needed to replace the original amount of plastic at the end of the waste treatment. In this section these results are commented and analysed in depth, with the purpose to fulfil the original aim, highlighting the most important parameters that influence the performances of the system, and to propose further useful researches, starting from the strengths and weaknesses of this project.

Analysis of results and significance of the study

Hypothesizing input data with low uncertainty, the model gives clear results in terms of variation of energy available in form of electricity and heat, both locally (see Figure 25 and Figure 26) and globally (see Figure 29). In general the model points out how an increased sorting of plastic waste for recycling (featured by Scenarios 2, 3 and 4) must be coupled with structural changes in the collection system, e.g. separate collection of PE, PET and PP, to produce good results, following the evaluated criteria. In fact, the separate collection helps the recycling process in terms of quality of the outputs, allowing a substantial fossil fuels saving with the substitution of virgin raw materials with secondary raw materials to produce the new plastic packages or products.

Importance of the Collection System for Plastic Waste Sorted for Recycling

Between Scenario 2 and 3, both with high sorting rates, but the first with separate and the second with mixed collection, there are 10 kg/pers/year of fossil fuels use of difference (22 kg/pers/year for Scenario 2 and 32 kg/pers/year for Scenario 3), which represent roughly the 25% of the fossil fuels use for plastic production in the scenarios explored (roughly 27 kg/pers/year of plastic are consumed by the households, and in average, for each kg of plastic, 1.5 kg of fossil fuels are needed in the production system, which yields to 40 kg/pers/year of fossil fuels for plastic production). These fossil fuels saved in the production system, if used for energy production, can compensate the energy that is not generated from incineration and even overcome these amounts.

These results are direct consequence of the fact that, while to produce plastics from virgin raw materials 1.5 kg of fossil fuels are needed, when incinerating 1 kg of plastic the yield in terms of energy generation is lower than the one of 1 kg of fossil fuels. Whilst the implications of this consideration seem to be obvious, this study shows how they are not trivial at all. This is visible in the comparison between Scenario 1 and Scenario 3, the ones that consider the mixed collection for plastic waste, where the increased sorting rates for plastic recycling, which are favouring the recycling stream (and the connected fossil fuels saving) are not producing remarkable results in the
aggregated evaluation. In fact, the corrected electricity available variation is just slightly higher in Scenario 3, while the heat generation is even lower. This is because the mixed collection, whose outputs are lower in quantity and in quality, does not allow a good level of substitution of the virgin raw materials.

**Importance of Plastic Waste Composition**

The collection method and the reprocessing are not the only important parameters in determining the performances of the system. Also the composition of the plastic waste plays an important role, lowering or increasing the amount of plastic waste that can be recycled effectively (some of the polymers are not easily recyclable, e.g. PS and Others). However, at least in the scenarios with separate collection, this element, while decreasing the overall performances of the recycling plants (see results for Scenario 2 in comparison with Scenario 4), does not make incineration more preferable than recycling. On the contrary, if the plastic waste generation was changing even more, lowering dramatically the amount of plastic that is recyclable, incineration would become the most preferable option. In fact, in this case, even if the plastic was sorted for recycling, it would have had anyway to be incinerated, and parameters like the increased energy for the collection and transportation, which have not been considered in this study because their impact is usually negligible, would have become crucial.

**Control on Incinerators’ operability and influence of other parameters**

The presented results hold just if the waste handling facilities can work efficiently with the considered material inputs. In this sense the stricter control has been done on the incineration process, checking the characteristics of the mixed household waste (heating value and moisture level mainly) to guarantee a good combustibility in all the scenarios. In the evaluated scenarios, the waste characteristics have been proven to be always at acceptable levels, similar or better than in the Base Case. In fact, the heating values are always very close to the design value (10 MJ/kg), and the moisture levels are far from the limit condition (50%). However this is also consequence of other assumptions made, not regarding the plastic waste. Above all the food sorting at 50% and the constant supply of industrial waste are fundamental to maintain the quality of the mixed household waste high enough for the combustibility without auxiliary fuels.

Without food sorting (see Figure 33), the plastic waste handling becomes decisive in warranting heating values close to the design one. The situation becomes even more dramatic for the incineration process removing also the industrial waste (see Figure 34), resulting in bad quality fuel independently on the level of plastic waste contained in the mixed household waste. There is a variation of almost 2 MJ/kg among the considered scenarios, but even in the best case, the heating value would be too low. It has to be said that the moisture level never reaches values higher than 50%, but the heating values are around 6-7 MJ/kg, very distant from the design heating value, precluding in any case an efficient operability.
Limitations of the study and possible future works

The model seems to be able to give indications regarding the functioning of the facilities involved in the plastic waste handling when changing the plastic waste generation and collection. The separate collection of some plastic polymers seem to be promising, while the incinerators should run without problems even with drastic changes in the plastic waste handling, unless the food sorting is not applied or the supply of industrial waste as auxiliary fuel is reduced. Nonetheless there are many
other elements that could be interesting to analyse, which can decrease the significance of the results of this project.

**Validation of Model’s Results needed**

For example, the importance of the separate collection of plastic waste has been related in this study to the improvement of the quality of the secondary raw materials. The relevance of the use of secondary raw materials to substitute virgin plastics has been proven to enhance the sustainability of the system in some of the reviewed studies (Finnveden et al. 2005). The likely changes in the waste generation, with a forecasted increase of plastic use for packaging, give even more importance to this aspect. However no reliable validation of this reasoning is carried out in this study. The example of the separate collection for PET bottles, with consequent bottle to bottle recycling and high substitution rates of virgin raw materials, is not enough, representing the bottles just one part of the overall plastic waste. In this sense it would be interesting to study the outcomes (in terms of virgin plastic substitution by secondary raw materials) of other waste management systems where the separate collection for all the packaging fractions has already been set, like for the collection system in Alberta, Canada (BottleBill 2010).

**Further Components that can be included**

In addition, the general uncertainty of the data used in this study precludes the usability of these particular results directly in the decision-making, as shown in the section related to the uncertainty of the results. However, even considering the feeding the model with more reliable data, there are several other aspects of the modelling itself that could be enhanced to increase its usability. The ones regarding the plastic recycling system are:

- Feedstock recycling for plastics;
- Substitution of plastics from fossil fuels with bio plastics;
- Impact of waste collection system on the workers, on the households and on the energy use and on the quality of the recyclables;
- Adaptability of current plastic recycling facilities to different plastic waste streams.

This is because in this study no recycling processes other than the mechanical reprocessing (which requires simply melting down plastic waste cleaned and with homogeneous composition) have been considered, while in the next years the feedstock or chemical recycling could change the importance of the parameters in the recycling system, since the outcomes should be more resilient to the quality of the input in terms of mixing and dirtiness (Lofti 2012). Also the increase of use of bio-plastics can change the picture, making the plastic system independent from the fossil fuels, but dependent on other resources, and lowering the constraints in terms of reliability of the waste collection, being the bio plastics biodegradable.
Talking about the consequences of the collection system in addition to the secondary raw materials quality, some studies have already been carried out (Palm 2009), but not on the typology of collection proposed. Therefore another study could focus on this aspect, analysing the impact of a separate collection system on households, collection spaces and transportation needed. Finally, also the flexibility of the recycling facilities is an issue, since a different collection system would require a different recycling process.

Considering instead the incineration facilities, the main component that would be interesting to study is the influence of waste characteristics on the incinerators’ efficiency and on the amount of auxiliary fuel to be used to support the combustion. In fact, in this study, when the combustibility of waste was granted by the average heating value and moisture level, the efficiencies in energy production have been taken as constant. Luckily in all the scenarios considered the characteristics of the waste are always good enough, because if it would have not been the case, from one side, if no auxiliary fuels are used, no implications on the efficiencies are known precisely, while if auxiliary fuels can be used, no straightforward estimations can be done. Even assuming to increase the supply of industrial waste, the consequences of this choice cannot be followed upstream and downstream with this model (and this is the reason why in this project the amount of industrial waste used in the incineration facilities has been kept constant in respect to the Base Case).
Conclusions

The aim of investigating specifically the effects of the future plastic waste generation and handling is met only partially because of the general uncertainty of the data used in the modelling. However, independently from the data set used to run the model in this study, the modelling has succeeded in highlighting the most important parameters in the plastic waste handling system, which are plastic waste composition and collection system, and the influence of plastic waste in the incineration process. In addition, the model has shown a moderate potential in supporting the decision-making at several societal levels once fed with good input data, unless the plastic waste handling is completely changing in the next years. In this case other studies would be required and other components should be added to the model (e.g. chemical recycling of plastic waste).

The plastic waste composition influences the effectiveness of any mechanical recycling system and therefore the outcomes of the system in terms of material and energy balances. The only treatment system that is not strongly affected by the plastic waste composition is incineration. However the model shows how energy recovery results in levels of energy available lower than the one offered by recycling when, in the plastic waste, some predominant fractions, homogeneous in terms of chemical composition, can be found, collected separately and recycled to be used again in the original applications. In this case the actual substitution of virgin raw materials, and the related saving of fossil fuels (which can be used in energy production in dedicated combined heat and power plants) makes recycling preferable. Therefore incineration is justified only for the plastic waste fractions that are not easily recyclable or whose composition is not constant in time.

These results highlight the need of a different legislation, both at National and European level, which does not focus only on the collection rates but helps the cooperation among the different stakeholders in order to make the recycling system and the production mutually consistent. In general the quality of the collected material (in terms of purity and absence of contamination for each polymer), instead of the amount, would be a good indicator for the effectiveness of a plastic waste handling system. In fact, the availability of waste fractions characterised by higher purity allows easier recycling processes and increases the willingness to recover it efficiently.

A good example is given by the PET bottles collected separately with a system based on deposits. That system, set mainly as solution to littering, has favoured the development of new technologies, like the URRC process, which allows the use of recycled PET again in food contact applications and hence boosts the virgin plastic substitution. The producers, having the chance to economise on the use virgin raw materials, accept willingly even to follow some general guidelines in the packaging production (which helps the collection system and the recycling process). The consumers, having to pay the deposit, give more value to the packaging itself and take care for its correct disposal. At the same time the municipalities could be appealed by the possibility to reduce their fossil fuels use.
Therefore the future plastic production has to be studied carefully in order to individuate the fractions that will unlikely experience dramatic changes. A new collection system could focus on these fractions and stimulate the action of recyclers for an efficient utilisation of the related waste streams. The Scenario 2 simulates this situation and the order of magnitude of the possible energy gain is not negligible. In fact, the 62 kWh/pers/year of variation in electricity available (thanks to the reduction in fossil fuels use of almost 11 kg/pers), if extended to the whole population of the County of Stockholm, represents more than 150 GWh/year, which overcomes the electricity production of turbine G1 in Högdalenverket (Fortum AB 2011), the one that is fuelled mainly with household waste.

In this panorama the increasing treatment capacity of the incineration facilities is not seen as an obstacle from the combustibility point of view since the food sorting could compensate the reduction of plastic in the mixed waste. However the effects of this trend should be analysed from other perspectives, above all considering the future availability of waste for importation and the related transport. In the model the effects of the transportation of the waste have been excluded but in the case of transportations for very long distances (1500 km) to import all the waste needed to fill the future treatment capacity, the related fossil fuels use is roughly 6 kg/pers. This component is not aggregated to the others because it would require also considering the characteristics of the waste imported and this is clearly outside the boundaries considered. However this evaluation can be helpful to get a sense of the impact of what has been excluded and of the importance of the different elements.

Summarising, the separate collection of 3-4 of the most important (in terms of amounts) and easily recyclable polymers (like PE, PET and PP), could lead to a general improvement of the plastic waste handling. However, because of the assumptions made in this project, further studies, highlighted in the discussion section, are needed to confirm or deprecate this proposal.
References

Laws


Others


Appendices

Appendix I - Specific Data Sources

To feed the model the data have been gathered from several sources, some of them already mentioned in the methodology chapter. Here the sources are clarified with a higher level of detail. In Table I, Table II and Table III the data and the related sources are listed.

Table I. Characteristics of Waste Fractions (several sources)

<table>
<thead>
<tr>
<th>Waste Fraction</th>
<th>Heating Value</th>
<th>Moisture Level</th>
<th>Ash Content</th>
<th>Combustible Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(MJ/kg)</td>
<td>(-)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDPE</td>
<td>25.3</td>
<td>0%</td>
<td>2%</td>
<td>98%</td>
</tr>
<tr>
<td>HDPE</td>
<td>40.1</td>
<td>0%</td>
<td>2%</td>
<td>98%</td>
</tr>
<tr>
<td>PET</td>
<td>21.6</td>
<td>0%</td>
<td>2%</td>
<td>98%</td>
</tr>
<tr>
<td>PP</td>
<td>40.1</td>
<td>0%</td>
<td>2%</td>
<td>98%</td>
</tr>
<tr>
<td>PS</td>
<td>37.6</td>
<td>0%</td>
<td>2%</td>
<td>98%</td>
</tr>
<tr>
<td>PVC</td>
<td>17.4</td>
<td>0%</td>
<td>2%</td>
<td>98%</td>
</tr>
<tr>
<td>Others</td>
<td>21.6</td>
<td>0%</td>
<td>2%</td>
<td>98%</td>
</tr>
<tr>
<td>Mixed</td>
<td>32.3</td>
<td>29%</td>
<td>8%</td>
<td>63%</td>
</tr>
<tr>
<td>Food</td>
<td>4.2</td>
<td>66%</td>
<td>13%</td>
<td>21%</td>
</tr>
<tr>
<td>Newspapers and office paper</td>
<td>18</td>
<td>47%</td>
<td>6%</td>
<td>47%</td>
</tr>
<tr>
<td>Paper Packages</td>
<td>16</td>
<td>0%</td>
<td>6%</td>
<td>94%</td>
</tr>
<tr>
<td>Other Paper</td>
<td>16</td>
<td>47%</td>
<td>6%</td>
<td>47%</td>
</tr>
<tr>
<td>Others Combustible</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Textiles</td>
<td>16</td>
<td>33%</td>
<td>4%</td>
<td>63%</td>
</tr>
<tr>
<td>Others</td>
<td>4</td>
<td>50%</td>
<td>9%</td>
<td>42%</td>
</tr>
<tr>
<td>Garden Waste</td>
<td>18</td>
<td>66%</td>
<td>13%</td>
<td>21%</td>
</tr>
<tr>
<td>Not combustible fraction (inert+glass+metal)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass Packaging</td>
<td>0</td>
<td>3%</td>
<td>97%</td>
<td>0%</td>
</tr>
<tr>
<td>Other Glass</td>
<td>0</td>
<td>3%</td>
<td>97%</td>
<td>0%</td>
</tr>
<tr>
<td>Metal Packaging</td>
<td>0</td>
<td>0%</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Other Metal</td>
<td>0</td>
<td>6%</td>
<td>94%</td>
<td>0%</td>
</tr>
<tr>
<td>Inert Waste</td>
<td>0</td>
<td>8%</td>
<td>92%</td>
<td>0%</td>
</tr>
<tr>
<td>Others</td>
<td>0</td>
<td>5%</td>
<td>95%</td>
<td>0%</td>
</tr>
<tr>
<td>Industrial Waste</td>
<td>20</td>
<td>10%</td>
<td>5%</td>
<td>85%</td>
</tr>
</tbody>
</table>

(U.S. Department of Energy 2007), (C-Tech Innovation Ltd 2003), (Rand et al. 2000), (Worrell & Vesilind 2012), (averages of other values), (Silfverduk & Carlberg 2011), (Process Combustion Corporation 2012)
Table II. Fossil Fuels Used Plastic Production (PlasticsEurope 2008)

<table>
<thead>
<tr>
<th>Resources for Production</th>
<th>(kg oil/kg plast)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDPE</td>
<td>1.59</td>
</tr>
<tr>
<td>HDPE</td>
<td>1.60</td>
</tr>
<tr>
<td>PET</td>
<td>1.64</td>
</tr>
<tr>
<td>PP</td>
<td>1.56</td>
</tr>
<tr>
<td>PS</td>
<td>1.40</td>
</tr>
<tr>
<td>PVC</td>
<td>1.15</td>
</tr>
<tr>
<td>Others</td>
<td>1.49</td>
</tr>
<tr>
<td>Mixed</td>
<td>1.49</td>
</tr>
</tbody>
</table>

Table III. Other data

<table>
<thead>
<tr>
<th>Data</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating value of oil</td>
<td>42 MJ/kg (World Energy Council 2012)</td>
</tr>
<tr>
<td>Fuel Consumption of Trucks</td>
<td>14.3 g oil/tkm (Carlsson 2002)</td>
</tr>
</tbody>
</table>

Appendix II - Waste Generation and Sorting - Base Case Evaluation

Here the derivation of the base case inputs, from which the different scenarios are derived, is explained. Since the method used to determine the average characteristics of the waste is based on a compositional analysis, the composition of the waste has to be known.

Data on Mixed Waste Generation

The categorisation of the different waste fractions has been done following the one used for the picking analyses carried out periodically on the mixed household waste in the municipalities in the County of Stockholm (Silfverduk & Carlberg 2011). This is because the picking analyses are a main source for data on mixed waste composition. This classification works also for the determination of the average characteristics of the waste. In fact they are quite homogeneous within these different fractions (almost the same categories are used in literature to report heating values, moisture contents, ash and combustible fractions, (Rand et al. 2000)). For example the different kinds of paper have different heating values, but the range of variation around the average heating value is quite narrow (+/-10%) (Worrell & Vesilind 2012).

In Table IV the results of the picking analyses for the City of Stockholm are shown for the year 2011 (Silfverduk & Carlberg 2011). The percentages are representing, for the different waste fractions, the shares ($W_{toEinPA}$) in the overall amount of waste to incineration.
Table IV. Composition of Mixed Waste – Pickling Analysis City of Stockholm

<table>
<thead>
<tr>
<th>Waste Type</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food waste</td>
<td>37.6%</td>
</tr>
<tr>
<td>Newspapers and Office Paper</td>
<td>8.0%</td>
</tr>
<tr>
<td>Paper Packages</td>
<td>9.6%</td>
</tr>
<tr>
<td>Plasti Packages</td>
<td>8.9%</td>
</tr>
<tr>
<td>Other Paper</td>
<td>7.9%</td>
</tr>
<tr>
<td>Other Plastics</td>
<td>3.9%</td>
</tr>
<tr>
<td>Textiles</td>
<td>2.0%</td>
</tr>
<tr>
<td>Other Combustibles</td>
<td>7.5%</td>
</tr>
<tr>
<td>Garden Waste</td>
<td>2.8%</td>
</tr>
<tr>
<td>Glass Packaging</td>
<td>3.9%</td>
</tr>
<tr>
<td>Other Glass</td>
<td>0.6%</td>
</tr>
<tr>
<td>Metal Packaging</td>
<td>1.5%</td>
</tr>
<tr>
<td>Other Metal</td>
<td>0.5%</td>
</tr>
<tr>
<td>Inert Waste</td>
<td>2.0%</td>
</tr>
<tr>
<td>Other not Combustibles</td>
<td>3.2%</td>
</tr>
<tr>
<td>Haz. Waste, Electronic waste</td>
<td>0.8%</td>
</tr>
</tbody>
</table>

At this point, knowing the amount of waste sent to incineration in the County of Stockholm and the population of the County itself (STAR 2011), the amount of waste produced in average by each household ($WtoE$) can be determined. The starting data are shown in Table V.

Table V. Statistics on Incinerated Waste – County of Stockholm

<table>
<thead>
<tr>
<th>Unit</th>
<th>Year 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population (people)</td>
<td>2.10E+06</td>
</tr>
<tr>
<td>Total Waste Incinerated (tons)</td>
<td>498080</td>
</tr>
<tr>
<td>Per-Capita Waste Incinerated - WtoE (kg/person)</td>
<td>237</td>
</tr>
</tbody>
</table>

At this point, from the last value computed and the picking analysis, the average amount of waste to incineration detailed per waste category of each household ($WtoE_i$) can be calculated.

$$WtoE_i = WtoEinPA\%_i \cdot WtoE$$  \hspace{1cm} (1)

For the plastic waste, being the focus of the study, a breaking down based on the composition can be useful, above all for the packaging fraction, in order to be able in the second sub-model to evaluate the effects of different collection systems. The splitting is based on the most common polymers used for packaging applications. This holds just for plastic used in packaging. The exact composition of the plastic not used for packaging is not considered because its variation is not influencing the evaluation of different choices in the recycling system. While a different collection
system based on the separation of the packaging waste based on composition could be set-up, it is very unlikely that a similar system could be set-up for the other plastics because of its more varied nature.

In this case, as input data, the European shares of the different polymers ($%Pol_k$) in the packaging production have been used. In Table VI the values used for this study are shown (Mudgal et al. 2011). The only modification has been done to lower the share of PET, since the biggest amount of that polymer is used for the beverages bottles, managed in Sweden with the deposit system. This system allows high recovery rates (Mattsson et al. 2009) and therefore these packaging have not been considered in the study.

Table VI. European Shares for Plastic for packaging

<table>
<thead>
<tr>
<th></th>
<th>Amount</th>
<th>Amount excluding 75% PET</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDPE</td>
<td>32%</td>
<td>36%</td>
</tr>
<tr>
<td>HDPE</td>
<td>19%</td>
<td>21%</td>
</tr>
<tr>
<td>PET</td>
<td>15%</td>
<td>4%</td>
</tr>
<tr>
<td>PP</td>
<td>19%</td>
<td>21%</td>
</tr>
<tr>
<td>PS</td>
<td>9%</td>
<td>10%</td>
</tr>
<tr>
<td>PVC</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Others</td>
<td>3%</td>
<td>3%</td>
</tr>
</tbody>
</table>

Using these data, the actual amount of each $k^{th}$ plastic polymer in waste can be evaluated:

$$WtoE_k = %Pol_k \cdot WtoEinPA_{plastic} \cdot WtoE$$  \hspace{1cm} (II)

All these values are representing the wet amounts of waste. The moisture coefficients ($M$) have to be used to determine the dry amounts of waste:

$$WtoEd_i = (1 - M_i) \cdot WtoE_i$$  \hspace{1cm} (III)

The packaging fractions are also contaminated by food waste. Therefore dirtiness coefficients ($DC$) have been considered and the amount of food waste has been increased consequently, while the packaging fractions have been assumed to be dry after this correction ($M = 0$):

$$WtoEd_{i-packing} = (1 - DC_i) \cdot WtoE_{i-packing}$$  \hspace{1cm} (IV)
Add \( W_{toEd_{food}} = \sum W_{toE_{i-packaging}} - W_{toEd_{i-packaging}} \) (V)

In Table VII are shown the dirtiness coefficients used in this study.

<table>
<thead>
<tr>
<th>Material</th>
<th>DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic Packages</td>
<td>37%</td>
</tr>
<tr>
<td>Paper Packages</td>
<td>37%</td>
</tr>
<tr>
<td>Metal Packages</td>
<td>27%</td>
</tr>
</tbody>
</table>

Now, wanting to know the total waste generation, the waste sorted for recycling has to be added to each waste fraction. In Table VIII the amounts of packaging waste collected for recycling are shown.

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Year 2011 (kg/pers/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newspapers</td>
<td>38.9</td>
</tr>
<tr>
<td>Paper Packages</td>
<td>7.5</td>
</tr>
<tr>
<td>Plastic Packages</td>
<td>2.7</td>
</tr>
<tr>
<td>Glass</td>
<td>27.1</td>
</tr>
<tr>
<td>Metal</td>
<td>1.1</td>
</tr>
</tbody>
</table>

However not for all the waste fractions these data are useful or available. Therefore when no information is available or when the sorting is assumed to not undergo negative trends (e.g. hazardous waste, food waste), the starting recycling rate is set at zero. On the contrary when data are available, the recycling rates \( RR_i \) are computed.

\[ RR_i = \frac{WSd_i}{WSd_i + WtoEd_i} \] (VI)

With the values just computed, the outputs for the base case can be evaluated, using the calculations showed for the sub-model 1.

**Appendix III - Model for Recycling Process**

In this appendix the model for the recycling process is explained, starting from the material inputs, passing through the system parameters (influenced by the technology available now or in the next...
future) and reaching the desired outputs that can be used to characterise the recycling step in the main modelling executed in this project.

**Inputs**
The plastic fractions collected for recycling constitute the material inputs.

**Outputs**
The aim of this model is to be able to estimate for each plastic waste fraction three fundamental parameters to portray the recycling sub-model, which are:
- The electricity consumption from the beginning to the end of the recycling process;
- The material loss, i.e. the amount of plastic that is sent to energy recovery because rejected during the recycling process;
- The virgin plastic substitution coefficient.

**System Parameters**
The parameters that are influencing the outputs are mainly related to the following aspects:
- Collection system for the plastic waste;
- The steps of the recycling process;
- The technology level of the equipment used.

The considered collection systems are:
- Mixed for all the plastics;
- Dedicated collection for certain plastic waste fractions (e.g. HDPE containers).

The collection system, as already mentioned in the main body of the report, influences strongly the recycling process.

The recycling processes to be taken into account as options have been selected reviewing one of the studies cited in the WRAP report on recycling 2010 (Shonfield 2008). The study considers different treatment options for the same mixed plastic waste, evaluating them with the LCA method. The collection systems are not considered, the inputs are constant and therefore its results cannot be used in this project as they are. However several recycling processes are explained and actual machinery is considered for the evaluations. Of this equipment the performances are also detailed in terms of electricity use, separation efficiency (for the separation machines) and material loss. Therefore this document provided a good starting point to run the model.

Although the technology level considered in the reviewed literature is the highest available now, in a forward looking study also changes in the technology level should be accounted. Hence the performances of the recycling processes have been assessed also applying likely effects of the forthcoming technologies.
Recycling Steps

The recycling process can be split into several sequential operations. The most common pattern is composed by the following steps:

- Hard/soft plastics separation;
- Sorting of the different plastic fractions;
- Shredding;
- Cleaning/Washing;
- Other treatments;
- Production of pellets.

While some of these steps are based on well-established and developed technologies (e.g., shredding and production of pellets), some others have experienced radical changes in the last years, trying to catch up with the requirements of the system. In the next sub-chapters some examples are presented.

Sorting of the different plastic fractions

Since the actual system is based on the collection of all the kinds of plastics, composition-wise, together, one of the biggest challenges is in the sorting step. The most common separation techniques nowadays are mainly based on the following principles:

- Difference in density;
- Difference in reflectivity within a wavelength range of 1100 to 2100 nm (Near Infrared sorting, NIR);

The NIR method is used for its versatility (it can recognise any type of plastic), while the density sorting, although not effective when the densities of the polymers overlap, is used for its high recovery rates (Shonfield 2008).

One of the possible forthcoming changes in the sorting is the possibility to sort the plastic waste in function of its colour. This technology is already used by a company in US (Envision Plastics) on the HDPE. This yields in a higher quality of the output, since the pellets are produced in different colours (while normally they are grey or black) and they can be used directly in new production processes without adding any colorant (Envision Plastics 2012). Unluckily no data are available regarding the performances of this technology.

Other treatments

One of the biggest limits of the actual recycling of plastics is the limited number of applications for these secondary raw materials. The 40% of the plastic is used for packaging (Mudgal et al. 2011), mainly for food packaging. However, at the moment, many of the secondary raw materials obtained recycling packaging cannot be used for food contact applications. Moreover, the polymers that are not used for packaging have usually different compositions from the ones used for packaging (Mudgal et al. 2011). Therefore, to boost the substitution of virgin raw materials with secondary raw materials, the most important challenge is to improve the quality of the secondary raw materials to allow the use of these materials back in the same market from where they come.
New technologies have already been developed lately and some of them are used nowadays with success. The most important example is the URRC process used by Cleanaway to recycle the PET bottles, coming from the collection of containers for beverages (managed with the deposit system), back into PET bottles (Cleanaway PET Svenska AB 2012). The fact that Envision Plastics have developed a similar technique also for HDPE (Envision Plastics 2012) shows that this technology might be available for almost all the polymers in the future.

Data Used
In Table IX, Table X, Table XI and Table XII the energy use and the material efficiencies of the equipment considered in the reviewed study (Shonfield 2008), and used to estimate the overall performances of different recycling processes are shown.

Table IX. Electricity Consumption and Separation Efficiency of the main sorting technologies for plastic waste

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Density Sorting</td>
<td>27.23</td>
<td>98%</td>
<td>98%</td>
<td>98%</td>
<td>98%</td>
<td>98%</td>
<td></td>
</tr>
<tr>
<td>Hard NIR Sorting</td>
<td>36.00</td>
<td>90%</td>
<td>80%</td>
<td>80%</td>
<td>60%</td>
<td>90%</td>
<td></td>
</tr>
</tbody>
</table>

Table X. Electricity Consumption and Separation Efficiency for the Hard/soft plastic separation

<table>
<thead>
<tr>
<th>Working Principle</th>
<th>Electricity Consumption (MJ/ton)</th>
<th>Sep. Efficiency</th>
<th>Mis-Sorting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film Removal</td>
<td>4.34</td>
<td>98.70%</td>
<td>11.20%</td>
</tr>
</tbody>
</table>

Table XI. Electricity Consumption and Material Loss for plastic cleaning technologies

<table>
<thead>
<tr>
<th>Work Principle</th>
<th>Electricity Consumption (MJ/ton)</th>
<th>Material Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Cleaning for Hard P.</td>
<td>90.00</td>
<td>10%</td>
</tr>
<tr>
<td>Dry Cleaning for Soft P.</td>
<td>360.00</td>
<td>10%</td>
</tr>
</tbody>
</table>

Table XII. Electricity Consumption and Material Loss for other steps in the recycling process

<table>
<thead>
<tr>
<th>Electricity Consumption (MJ/ton)</th>
<th>Material Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shredding</td>
<td>86.40</td>
</tr>
<tr>
<td>Extrusion</td>
<td>972.00</td>
</tr>
</tbody>
</table>
**Assumptions and Simplifications**

Since the aim of this modelling is just to understand which are the important parameters and the orders of magnitude in terms of energy use and material yield of the processes, not all the recycling technologies have been considered.

**Calculations and Derivations**

After having designed the recycling process, the different outputs are derived starting from inputs and system parameters.

**Electricity Use**

The electricity use is estimated summing up the electricity consumption of each m\textsuperscript{th} recycling step.

\[ \text{Electricity for REC pmp}_i = \sum \text{Electricity for REC pmp}_m \] (VII)

**Material Loss**

The material loss depends also on all the recycling steps. However for the sorting stages just the separation efficiencies are available. The definition of separation efficiency is not clear from the source, but for simplicity it is assumed that it corresponds to the complementary of material loss. Therefore the overall material loss (MLC) can be computed as follows:

\[ MLC_i = 1 - \prod (1 - MLC_m) \] (VIII)

**Virgin Plastic Substitution Coefficient**

This value cannot be computed directly from the system parameters, but it depends on them. In fact, the better is the quality of the secondary raw materials, the higher the virgin plastic substitution value (Carlsson 2002). Since there are no data available on the actual use of secondary raw materials, they are estimated in function of the following elements:

- Values found in other studies (Carlsson 2002);
- Quality of the material collected for recycling, which depends on the collection system;
- Quality of the recycling process.

**Results**

Keeping in mind the aim of this modelling, just a few recycling processes are evaluated, trying to find the ranges of variation for electricity use and material loss. Being the equations that are describing the system’s behaviour quite simple, it is straightforward the derivation of the most interesting cases.
Recycling process for mixed waste

In Figure I a common recycling path for mixed plastic waste is depicted, focusing on just one fraction (e.g. HDPE), from the first to the last step of the recycling process. However, not all the polymers undergo the same treatment after the sorting. Some of them are more difficult to recycle (e.g. PS, others) and are usually considered as a reject and sent to energy recovery (Swerec AB 2012).

**Figure I. Recycling Process for HDPE in mixed plastic waste**

Recycling process for separated polymer (Basic)

In Figure II a simplified recycling process is shown. The higher purity of the incoming fraction allows a lower degree of complexity in the separation/sorting step. The polymer considered in this example is again HDPE.

**Figure II. Basic Recycling Process for HDPE from separated collection**

Recycling process for separated polymer (Advanced)

Taking into account the latest technologies for recycling, a more complex recycling process is detailed in Figure III. At the end of this process, the secondary raw materials are colour sorted and re-usable in food contact applications.

**Figure III. Advanced Recycling Process for HDPE from separated collection**
In Table XIII the results summarised:

Table XIII. Electricity Consumption and Material Loss for other steps in the recycling process

<table>
<thead>
<tr>
<th>Input</th>
<th>Process</th>
<th>Electricity Consumption</th>
<th>Material Loss</th>
<th>Virgin Plastic Substitution Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE in Mixed Fraction</td>
<td>Standard</td>
<td>1.39</td>
<td>32%</td>
<td>60%</td>
</tr>
<tr>
<td>PS in Mixed Fraction</td>
<td>Standard – Polymer Rejected</td>
<td>0.13</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>HDPE in Separated Collection</td>
<td>Basic</td>
<td>1.24</td>
<td>14%</td>
<td>70%</td>
</tr>
<tr>
<td>HDPE in Separated Collection</td>
<td>Advanced</td>
<td>1.44</td>
<td>26%</td>
<td>90%</td>
</tr>
</tbody>
</table>

The virgin plastic substitution coefficients are written in red to remind the high uncertainty on these values.