Life Cycle Assessment of Thermal Treatment Technologies

An environmental and financial systems analysis of gasification, incineration and landfilling of waste

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ABSTRACT

A technology which is currently developed by researchers at KTH is catalytic combustion which is one component of a gasification system. Instead of performing the combustion in the gas turbine by a flame, a catalyst is used. When the development of a new technology (as catalytic combustion) reaches a certain step where it is possible to quantify material-, energy- and capital flows, the prerequisites for performing a systems analysis is at hand. The systems analysis can be used to expand the know-how about the potential advantages of the catalytic combustion technology by highlighting its function as a component of a larger system. In this way it may be possible to point out weak points which have to be investigated more, but also strong points to emphasise the importance of further development.

The aim of this project was to assess the energy turnover as well as the potential environmental impacts and economic costs of thermal treatment technologies in general and catalytic combustion in particular. By using a holistic assessment of the advantages and disadvantages of catalytic combustion of waste it was possible to identify the strengths and weaknesses of the technology under different conditions. Following different treatment scenarios have been studied: (1) Gasification with catalytic combustion, (2) Gasification with flame combustion, (3) Incineration with energy recovery and (4) Landfilling with gas collection. In the study compensatory district heating is produced by combustion of biofuel. The power used for running the processes in the scenarios is supplied by the waste-to-energy technologies themselves while compensatory power is assumed to be produced from natural gas. The emissions from the system studied were classified and characterised using methodology from Life Cycle Assessment into the following environmental impact categories: Global Warming Potential (also called the green house effect), Acidification Potential, Eutrophication Potential and finally Formation of Photochemical Oxidants.

It is obvious that a decreased use of landfilling in favour of an increased energy recovery from waste is positive from all considered impact categories. Gasification with energy recovery in a combi cycle using catalytic combustion in the gas turbine is the most competitive technology from primarily an environmental point of view. The financial costs are however a bit higher than for incineration with energy recovery. This conclusion depends, however, on the assumption that the gasification and catalyst technologies work as the researchers presume and that the fuel is of high quality. For this, the pelletising unit is vital in the technology chain.

A comparison of the catalytic combustion and the flame combustion shows that all impact categories except acidification, eutrophication and photochemical oxidants remain the same. The gasification process is identical between the two alternatives; it is just the combustion technology in the gas turbine that is different. This explains why the fuel consumption and the financial costs are not changed (a minor extra investment is made for the catalyst but is not noticeable in comparison to the total impact). Emissions of greenhouse gases are also identical. For the other impact categories there are differences for several of the emissions involved in the impact assessment but NO_X is clearly the dominating one.

Gasification with catalytic combustion is competitive to incineration. The small difference for eutrophication is within the error margin and is strongly dependent on the reduction of NO_X in the incineration plant. The explanation to this result is that a combi cycle in combination with natural gas as the alternative power generation is a better system solution than incineration with biofuel as compensatory fuel. Financial costs are somewhat higher than for incineration but could also claimed to be within the error margin since the inventory of costs are more uncertain due to the fact that there is no plant with gasification and catalytic combustion in operation.

SAMMANFATTNING

Katalytisk förbränning är en ny teknik som utvecklas av bl.a. forskare vid KTH. Istället för att förbränningen i en gasturbin sker med flamma används en katalysator. Genom att göra så kan emissionerna av framförallt kväveoxider minskas drastiskt. När utvecklingen av en ny teknik som katalytisk förbränning kommer till en punkt där det är möjligt att kvantifiera material-, energi- och kapitalflöden finns förutsättningarna för att kunna belysa tekniken ur ett systemperspektiv. Systemanalysen kan användas till att öka kunskapen om fördelarna med katalytisk förbränning genom att belysa dess funktion som komponent i ett tekniksystem eller teknikkedja. På detta sätt är det möjligt att identifiera svaga punkter i kedjan som kräver ytterligare forskningsinsatser, såväl som styrkor vilka motiverar en fortsatt teknikutveckling.

Syftet med detta projekt har varit att beskriva energiflödena och den potentiella miljöpåverkan samt härtill förknippade kostnader för olika termiska avfallsbehandlingstekniker i allmänhet och katalytisk förbränning i synnerhet och jämföra dessa mot varandra och mot avfallsdeponering. Genom att göra en helhetsbedömning av fördelar och nackdelar med katalytisk förbränning vid avfallsbehandling har det blivit möjligt att identifiera teknikens styrkor och svagheter under olika förhållanden. Följande behandlingsscenarier har studerats: (1) Förgasning med katalytisk förbränning, (2) Förgasning med flamförbränning, (3) Avfallsförbränning med energiutvinning samt (4) Avfallsdeponering med gasuppsamling. I studien antas att den fjärrvärme som behövs för processer i systemet samt för att i förekommande fall ersätta avfallsbaserad fjärrvärme, genereras genom förbränning av biobränsle. Elektricitet som används av processer i systemet samt kompletterande elproduktion antas genereras genom förbränning av naturgas. Emissionerna från systemet har klassificerats och karakteriserats enligt metodik från livscykelanalys i följande miljöpåverkanskategorier: Växthuseffekt (global uppvärmning), Försurning, Eutrofiering (övergödning) och Bildning av fotokemiska oxidanter.

Det är uppenbart att en minskad avfallsdeponering som syftar till ett ökat energiutnyttjande från avfall är positivt ur alla här beaktade påverkanskategorier. Förgasning i en kombicykel där gasturbinen använder katalytisk förbränning är den mest fördelaktiga tekniken ur miljöperspektiv. De företagsekonomiska kostnaderna är dock något högre än för avfallsförbränning med energiutvinning. Slutsatsen baseras på antagandet att förgasnings- och katalysteknikerna fungerar som forskarna förutser och att bränslet håller en hög och jämn kvalitet. Av detta följer att pelletiseringen av avfall innan förgasning är en viktig del av teknikkedjan.

En jämförelse av katalytisk förbränning och flamförbränning ger vid handen att alla påverkanskategorier utom försurning, övergödning och bildning av fotokemiska oxidanter är lika för de två teknikerna. Förgasningsprocessen är lika för de två scenarierna, det är endast förbränningstekniken i gasturbinen som skiljer alternativen åt. Det förklarar varför bränsleförbrukningen och den företagsekonomiska kostnaden för emissionerna inte skiljer alternativen åt (katalysatorn medför en mindre extrainvestering som dock inte slår igenom i totalkostnaden). Emissioner av växthusgaser är också identiska för de två scenarierna. I övrigt skiljer sig emissionerna åt på en del punkter men den största skillnaden ligger i utsläpp av kväveoxider som är lägre för katalytisk förbränning.

Förgasning med katalytisk förbränning är konkurrenskraftig i förhållande till avfallsförbränning. En liten skillnad kan skönjas för övergödning (där förbränning ger lägre påverkan än förgasning) men är så liten att den ligger inom felmarginalen för analysen. Resultatet beror starkt av vilken typ av kväveoxidreducering som finns i förbränningsanläggningen. Att resultatet blir så här förklaras av att en kombicykel i kombination med naturgas som alternativt bränsle för elproduktion är en bättre systemlösning än avfallsförbränning med biobränsle som kompletterande bränsle för fjärrvärme. De företagsekonomiska kostnaderna är något lägre för avfallsförbränningen men skillnaden ligger även här inom felmarginalen eftersom inventeringsdata för kostnader är mer osäkra än emissionsdata. Detta beror på att ingen förgasningsanläggning med katalytisk förbränning existerar varifrån uppgifter skulle kunna ha hämtats.

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Understanding of the gasification and catalytic combustion technologies have been made easier by contacts with *Krister Sjöström* at the department Chemical Technology at KTH. Valuable information has also been obtained from staff at *Termiska processer AB* (TPS).

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1 INTRODUCTION

1.1 BACKGROUND

As new directives regarding waste management have been adopted in the EU (EU 1999, EU 2000), there will probably be an increased amount of waste going from landfilling to incineration. In Sweden a landfill tax of 280 SEK/ton is already in place (will be increased to 370 SEK/ton) and a total ban on landfilling of combustible waste (SFS 1998:902) was introduced this year, 2002. This implies that Swedish municipalities now will have to develop mechanisms for waste source separation and a more advanced and diversified waste management.

Today, Sweden has 22 incineration plants and more incinerators are now planned for. In Sweden incineration is combined with energy recovery, mainly as district heating but also generating electrical power. The technology is well established and with advanced flue gas cleaning and condensation, the plants have high prestanda in terms of environmental performance and degree of efficiency. In comparison to incineration, gasification and combined cycles (a gas turbine in connection to a steam turbine) are not commonly used in Sweden. Internationally, gasification is gaining acceptance but municipal waste is a rarely used fuel in these applications. By gasification of the waste and then combustion of the product gas in a combi-cycle gives an economic advantage in comparison to conventional combustion, since higher electricity efficiency is obtained.

A technology which is currently developed by researchers at KTH is catalytic combustion which is one component of the gasification system. Instead of performing the combustion in the gas turbine by a flame, a catalyst is used. When the development of a new technology (as catalytic combustion) reaches a certain step where it is possible to quantify material-, energy- and capital flows, the prerequisites for performing a systems analysis is at hand. The systems analysis can be used to expand the know-how about the potential advantages of the catalytic combustion technology by highlighting its function as a component of a larger system. In this way it may be possible to point out weak points which have to be investigated more, but also strong points to emphasise the importance of further development.

1.2 PROBLEM

The most obvious benefit of using a catalytic combustion in favour of flame combustion is the lower emissions of nitrogen oxides. These lower emissions have, however, not yet been quantified and compared from a systems perspective which is a problem if the technology should be evaluated with a life cycle perspective. Also, other benefits in terms of lower emissions are not so well described and above all not assessed in a broader scope. It is also unclear which are the drawbacks and how big or small are they? The strong and weak points of the technology chains have not been investigated so far. All these problems have not become problems until now when the technology development is as promising as it is. It is also a fact that the specialists in catalyst technology lack of a good tool for an LCA of the product under development. In particular systems analyses comprising both ecological and economical assessments are in this regard rare but helpful. With a life cycle perspective it is possible to compare future technologies with existing and evaluate environmental impacts arising today or in the future.

1.3 PROJECT AIM

The aim of this project was to assess the energy turnover as well as the potential environmental impacts and economic costs of thermal treatment technologies in general and catalytic combustion in particular. By using a holistic assessment of the advantages and disadvantages of catalytic combustion of waste it was possible to identify the strengths and weaknesses of the technology under different conditions. An underlying aim in this sub-project was to develop and test the ORWARE model in a new application area, namely Technology Assessment (TA; cf. Assefa et al., 2002). Thus, the project was also expected to bring about an experience of new application areas for the ORWARE model. This could later be utilised in other technology assessment applications of similar character.

2 THERMAL GASIFICATION OF MUNICIPAL SOLID WASTE

The most important reason for gasification of waste is that a higher electricity production is possible. The overall degree of efficiency (electric + thermal) is somewhat lower than for a CHP process (Combined Heat and Power) but with an α-value of about 1, it may still be profitable. The most promising application of thermal gasification in waste management is atmospheric gasification. The information given in this chapter is based on Dahlroth (1999).

2.1 GASIFICATION IN GENERAL

Gasification is combustion with a strong air deficit. The combustion is very incomplete and the combustion gas will contain of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2) and other tar gases to such a high degree that the gas will become combustible. There is also some carbon dioxide (CO_2) as some combustion has to take place in order to obtain the heat needed for the gasification process. There is also nitrogen (N_2) from the combustion air, water vapour (H_2O) and small amounts of nitrogen compounds as ammonia (NH_3) and cyan (C_2N_2 or CN).

The chemical composition and the heat value of the gas mixture are heavily dependent on the gasification temperature, which in turn depends on the air and water content of the fuel. Instead of using air, pure oxygen or oxygenated air could be used. Then, the gasification may take place at a higher temperature and the gas formed will have a higher concentration of hydrogen and higher heat value. The method is, however, more expensive. A high hydrogen concentration and a high heat value are preferable if the gas is to be combusted in a gas turbine.

Apart from an increased power production, the possibility to clean the gases before combustion is pointed out as an advantage of gasification compared to combustion. Sulphur (S) can be removed as well as ammonia and cyanides. The gas will also contain a very low concentration of nitrogen compounds that result in low emissions of NO_X. For municipal solid waste, sulphur is no big problem and the heat value of the gas is low which results in a low NO_X formation. Here, the possibility to clean the gas from chlorides is of higher importance. This is since alkali metals should be removed from the gas in order to protect the gas turbine used after the gasification step. In this gas cleaning scrubber, there is also a possibility of removing heavy metals.

A third reason for working with gasification is that the temperature in the reactor can be maintained at a high level – as long as the fuel is not to wet – resulting in a melted ash that can easily be removed at the bottom of the reactor. The melted ash may be cooled into almost inert gravel with poor leachability characteristics, which can be used as a filling material and for road construction.

2.2 GAS TURBINE OR STEAM BOILER

If the gas is to be used in a gas turbine, the fuel should have low moisture content, below 25 % (cf. Dahlroth, 1999). For household waste this limit is probably even lower due to a high part of inert material in this type of waste (See waste composition in Chapter 11). Too much moisture in the fuel decreases the heat value of the gas, making it impossible to use it in a gas turbine. The demand for low water content in the fuel also means that waste which is to be gasified and used in a gas turbine normally must be dried. This is a disadvantage, since a dryer is a voluminous and expensive facility.

If the gas is to be combusted in a steam boiler, the moisture content can reach up to 50 % without any problems (cf. Dahlroth, 1999). Thus, it could be seen as a long and unnecessary way first to gasify the waste before energy recovery, but the combined advantages has a potential to overcome the drawbacks. Cost savings thanks to a higher electricity production and lower emissions could more than compensate for the more complex system design.

2.3 WASTE AS FUEL

Waste is appropriate for gasification. The organic compounds in the waste and plastic are chemically very reactive and easy to gasify. Problems in gasification of waste are mainly associated with moisture content and solid contaminants, i.e. the same problems as for direct combustion. The largest disadvantage of using waste for gasification is that the technology is relatively unproven. So far, most experience also indicates that the cost advantage compared to conventional technology not is big enough to motivate a change of technological approach.

2.4 THE TPS CONCEPT

Sweden has under the later part of 90s lagged behind other countries in the development of grate boilers for biofuel and waste. This means grate boilers have to be imported from countries in the technological front line. The concept of combining gasification and catalytic combustion gives the advantage of using Swedish gasification technology. The Swedish company TPS AB has developed a considerable know-how in this area. A TPS designed waste gasification facility in northern Italy has been used as a source of data in this project. The Italian facility consists of two gasifyers of totally 15 MW fuel (Morris and Waldheim, 1998). The fuel is pellets made of waste with a moisture content of 3-4 %. The heat value is 1.9 kWh/ m^3. As the gas is directly combusted in a boiler, no cracker for tar removal is needed. After the combustion the flue gases is cleaned by injection of dry chalk in the gas stream and subsequent treatment in a textile filter.

The special characteristics of the TPS method are that two circulating fluid beds are used in series. In the first one, gasification takes place. The resulting gas has a pressure of about 1.6 Bar and a temperature of about 850 °C when it leaves the gasifyer and enters the second step - the tar cracking plant. Here, the main part of the bed material consists of the mineral dolomite that has a catalytic, degrading and dissolving effect on the tar gases formed during the gasification. It is important to dissolve the tar particles if the gas is to be cooled down before further cleaning. Tests have shown that chlorine in the waste has a negative impact on the cracking reactions. If the gas is combusted directly in a steam boiler without any form of pre-cleaning, extensive cleaning equipment has to be installed after the boiler, similar to direct waste incineration. In the TPS gasification system followed by direct combustion, an α-value of 0.46-0.50 and an overall efficiency of 88 % can be reached. More realistic is, however, efficiency below 85 %. The numbers are for dried waste fuel and potential losses in the drying are not included. Gasification of waste in a circulating bed does not give a vitrified ash but an ash type with poorer environmental characteristics and incompletely combusted carbonaceous material. The leaching characteristics of this ash in landfilling are not known, but supposedly the ash may cause problems.

2.5 GAS CLEANING

Heavy metals with a low boiling temperature - such as lead – will be vaporised to a great extent. The metals will join the gas stream and end up in the flue gas cleaning equipment. The formation of dioxins, dibensofurans and other halogenic hydrocarbons is limited thanks to the high temperature. During start-up and stops of the facility, however, formation rates may be higher. Here, an advantage with gasification is that the gas volume to be cleaned is much smaller than the volume after a normal combustion of the fuel.

The gas has to be cooled to be cleaned. Heavy metal fumes will condensate or be absorbed chemically in the different washing steps at hand. Unfortunately, the washing of the gas results in a lower steam production. A quick cooling can not take place in an ordinary heat exchanger. Water has to be injected to the gas or it has to pass a fluid bed with built-in cool pipes. If the gas is not cleaned, the same type of cleaning equipment as after incineration on roster or fluid bed has to be used after the combustion of the gas in a gas turbine.

2.6 ADVANTAGES AND DISADVANTAGES

Certainly gasification is more expensive than conventional technologies. In order to use the gases from conventional technologies in direct turbine applications, however, particles and specific pollutants should be

removed to guarantee a safe operation. The advantage of catalytic combustion is mainly the extremely low NO_X emissions. Besides this, it has other advantages, such as a good tolerance to variations in fuel/air ratio and its ultra low emissions of UHC (Uncombusted HydroCarbons) and CO. Thus, the use of catalytic combustion after gasification is more environmentally friendly than direct combustion. A summary of what was mentioned above is found in Table 2.1.

Table 2.1 Evaluation of the gasification technology

Advantages	Disadvantages
+ Waste is appropriate for gasification	- The overall degree of efficiency is somewhat lower than for CHP
+ Higher electricity production than direct incineration	- The method is not well proven yet
+ The possibility to clean gases before the combustion	
+ The gas volume to be cleaned is much smaller than the volume after a normal combustion of the fuel.	
+ Low emissions of e.g. ammonia, nitrogen oxides and chlorine	

2.7 APPLICATIONS

Catalytic combustion is gaining significance in USA and Japan. This has so far been related to catalytic combustion of natural gas. Catalytica in USA has already a commercial facility for catalytic combustion of natural gas with an emission of lower than 3 ppm NO_X.

The municipality of Kil is located in southern Värmland 20 km north of Karlstad. The densely populated area accommodates around 13 000 people. The municipality has since the 70s been strongly working with energy issues and possibilities of using local bio energy for heating purposes. Kils Energi AB was established in 1983, as full municipal energy company, got the responsibility to plan and carry out establishment of a new local energy system mainly based on biofuel. The municipality of Kil got substantially expanded with new villa areas where heating is distributes dominantly as electricity. In 1996 Kil had 2000 villas with direct electricity heating (70s) and waterborne electricity heating (80s). A new energy directive adopted in 1987 prohibited further construction of electricity heating systems and required the creating of new alternatives that could substitute electricity heating in the future. When the municipality of Kil planned to start construction of new centre in new area called Kilslund Kils Energi AB was given the task of presenting and afterwards implementing an alternative to electricity heating. The new area is planned for about 500 flats.

There is large amount of combustible waste in the region but there is no combustion facility adapted for it. Kils Energi AB had a plan to build a combustion facility for sorted combustible waste in line with the demand for district heating that exists in the densely populated area. The facility is supposed to have an effect of app. 8 MW heat. TPS AB, Termiska Processer i Studsvik AB, was to analyse on how to optimise the design of the boiler in terms of environmental considerations. The facility will start operating in April 2003.

3 CATALYTIC COMBUSTION

3.1 GENERAL INFORMATION

Catalytic combustion is a relatively new development of flame combustion. The flame combustion technology has been in use for so long that different improvements have been introduced regarding emissions and combustion efficiency. The catalytic combustion technology on the other hand, has implications beyond emissions and combustion efficiency. It operates at a relatively low temperature and with a high degree of control. Different fuels ranging from natural gas to gasified coal have been used in flame combustion technology in gas turbine applications (Borman and Ragland (1998), Sydkraft (2001), Beer (2000)). When catalytic combustion came into the scene, natural gas was the fuel raising most interest in different experiments ranging from lab scale to pilot scale. Recent works on combustion (Tsuchiya (1997) and Johansson (1998)) has focused either on of flame versus catalytic combustion using a given fuel or different fuels using a given technology. The essential difference between the two approaches to gas turbine combustion is shown schematically in Figure 3.1.

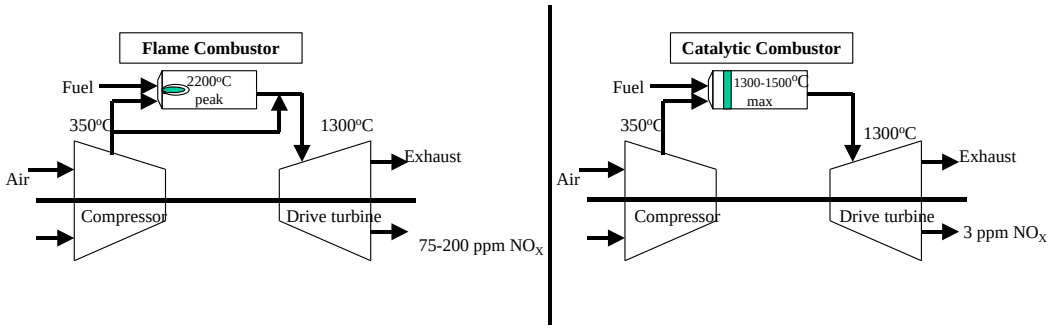

Figure 3.1 Essential distinguishing features of a flame versus a catalytic combustor

Despite the gas turbine's well-known benefits in distributed generation and cogeneration, the drawback related to the combustion process has hindered its wide use. In contrast to flame combustion, catalytic combustion does not involve any issues of flame stability. The fuel-air ratio entering the catalyst simply needs to be high enough to generate the desired turbine inlet temperature at full conversion of the fuel.

3.2 SYSTEM DESIGNS

Data and figure in the following parts of the text are from Catalytica Energy Systems (2002). Restrictions on emissions currently limit the firing temperatures, and hence efficiency, of gas turbines that power utility systems and industrial processes. Even the best of existing methods for limiting nitrogen oxide (NO_X) emissions have major drawbacks, such as high costs (Advanced Technology Program, 2000). A catalytic combustion system operates at significantly increased temperatures while also limiting NO_X and carbon monoxide (CO) emissions. Existing catalytic combustion systems, in which a catalyst is used to oxidize fuel until the gas stream reaches a temperature high enough for homogenous combustion, operate on natural gas only, requires a pre-burner (which contributes to NO_X emissions), and limits the extent of fuel conversion.

An advanced two-stage system operating on natural gas and liquid fuels is also one possible model. The first stage operates at low temperatures, initiating the catalytic reaction without a pre-burner, and converts natural gas or liquid fuels into a highly reactive lean mixture. The second stage will have a high-temperature catalytic combustor operating at moderate to maximum flame temperatures (1260-1570 ºC), enabling full fuel conversion and minimizing NO_X and CO emissions. The low and high ends of the temperature range represent applications for small industrial and large utility gas turbines, respectively. Major technical challenges include the design of a high activity catalyst for the first stage, and a stable ceramic oxide catalyst and support material for the second stage. High temperatures in a combustion process accelerate NO_X formation. The temperature dependence of NO_X production is shown in Figure 3.2 for conditions typical of a gas turbine combustor.

3.3 LOW FORMATION OF NITROGEN OXIDES

In current small turbines the required maximum temperature at the combustor exit is typically 1350°C or lower; so Figure 3.2 shows that extremely low NO_X concentrations are possible using catalytic combustion.

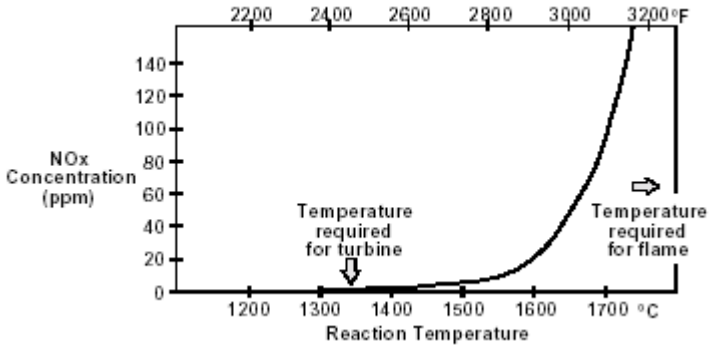

Figure 3.2 Dependence of NO_X formation on temperature (10 atm pressure, 20 ms residence time) [Catalytica, 2002]

It is evident from the curve in Figure 3.2 that NO_X production increases dramatically when the temperature exceeds about 1600°C (2900°F). Temperatures in the hottest regions of a diffusion flame can exceed 2200°C (4000°F) for brief periods, so there is a small possibility of achieving single digit NO_X levels when a turbine is fired with a diffusion flame combustor. If, on the other hand, the peak combustion temperature can be limited below about 1540°C (2800°F), NO_X levels can be lower than a few parts per million. Unfortunately, at fuel-air ratios low enough to achieve such low NO_X concentrations, flames are highly unstable and are susceptible to flame-out conditions or fluctuations which can cause severe combustor vibrations, so even a lean premixed combustor cannot operate in this most desirable low temperature range to achieve ultra-low NO_X emissions.

3.4 GAS CLEANING SYSTEMS

As a consequence of the situation depicted in figure 3.2, a gas turbine with a lean premixed combustor must use an exhaust gas cleanup system to meet low NO_X emissions. Selective catalytic reduction (SCR) technology is available for this purpose, but adds significant costs that are reflected in the cost per kilowatt-hour (i.e., the cost of electricity) that the end user ultimately pays. In addition, SCR systems require ammonia, which presents problems in transportation and storage due to its volatility and toxicity. Urea based SCR systems are an alternative, but they require an extra process step to convert the urea into ammonia for reaction over the SCR catalyst. SCONOX, a second commercial cleanup system, is even more expensive than SCR. The cost of an extra cleanup unit is particularly burdensome for smaller gas turbines, as the treatment costs are higher on a SEK-per-kilowatt and per kilowatt-hour basis.

4 METHOD

4.1 SYSTEMS ANALYSIS

Many of the problems in our modern society have emerged from interactions between humans, technology and natural environment. Such problems can often be addressed by a systems analysis approach (Miser & Quade, 1985). Systems analysis is not a well-defined methodology, but is rather an approach for evaluation and integrated analysis of complex systems (Björklund, 1998). According to Miser et al, 1995 "Systems analysis brings to bear the knowledge and methods of modern science and technology, in combination with concepts of social goals and equities, elements of judgement and taste, and appropriate consideration of the lager contexts and uncertainties that inevitably attend such problems". The aim of this kind of approach is to gain deep understanding of the problem and use it to help bring about improvements (Miser & Quade, 1985).

A system is a set of related entities that interact with each other in some way. Anything in nature or society may be described as a system consisting of sub-systems, and it self acting as a sub-system in a larger context (Björklund, 1998). By understanding the sub-systems and the linkages between the sub-systems and the main system, the effects of new decisions can be estimated. The sub-systems and their linkages can be described in a model, a simplified abstraction of the system. A computer model consisting of a mathematical description is often constructed (Björklund, 1998). The model can work as a tool to solve problems and as a support in decision-making and planning of complex systems.

Systems analysis is valuable in assessment of identified alternative methods of solving a clearly defined problem. This is since a decision-maker ought to know the consequences of alternative choices. The scope and objective of the assessment stem out from the functions that the identified alternatives can provide and account for the decision to be made using the outcome of the assessment. Within the domain of systems analysis, models are used to predict such consequences of taking up alternatives. A number of mental and implicit models, and other explicit models expressed by words, diagrams, mathematical equations etc., are synthesised to explicit models represented quantitatively and often expressed by computer programs. The impracticality, high cost and danger associated with full-scale test of each and every alternative back up the need for these models.

One model developed for calculating energy, environmental and economic performance for waste management systems in a life cycle perspective is called ORWARE (Organic Waste Research). Originally, the ORWARE model was developed for systems analysis of waste management (cf. Björklund, 2000), but the model has a potential to be used as a starting point for assessment of new technology such as catalytic combustion of gasified waste and to be used for assessment of other technical systems as well. In a previous project financed by Swedish Energy Administration, the model has been further developed with a focus on energy related waste management issues (Eriksson et al, 2000). The following part describes ORWARE as a tool for systems analysis of waste management using concepts of material flow analysis and LCA.

4.2 THE ORWARE APPROACH

4.2.1 General

ORWARE has a feature of Material Flow Analysis (MFA) (Baccini & Brunner, 1991). A material flow analysis describes the static situation of different materials flows between different subsystems in a defined system. The model handles a large number of physical flows and may therefore be characterised as a multidimensional material- and substance flow analysis (for substance flow analysis cf. van der Voet et al, 1995). Flows such as Total Solids and Polycyclic Aromatic Hydrocarbons (PAH) as well as single elements such as chlorine and copper may be followed. In the current form of the model, it is possible to evaluate the results from over 50 parameters simultaneously. In practice, however, the amount of parameters that may contribute in a meaningful way is lower due to lack of data or poor data quality. The MFA carried out in ORWARE generates data on emissions from the system, which is aggregated into different environmental

impact categories. This makes it possible to compare the influence of different waste management system alternatives on e.g. the greenhouse effect, acidification, eutrophication and other impact categories.

4.2.2 System Boundaries

The system boundaries are of three different types; time, space and function. In an analysis of a certain system, the temporal system boundaries vary between different studies (depends on the scope) and also between different submodels. Most of the process data used is annual averages but for two submodels (the landfill model and the arable land model) long-term impacts are also included.

There is a geographical boundary delimiting the waste management system, whereas emissions and resource depletion are included regardless of where they occur. The system boundaries in ORWARE are chosen with an LCA perspective, thus including in principle all processes that are connected to the life cycle of a product (in this case a waste management system). Our coverage of life cycle impacts covers raw material extraction, refinery, production and use. Construction, demolition and final disposal of capital equipment are not included regarding energy consumption and emissions but are included for economy. This is illustrated in Figure 4.1, which shows how a core system (the waste management system) is enlarged in order to include relevant upstream (e.g. energy generation) and downstream (e.g. biogas usage) activities and processes.

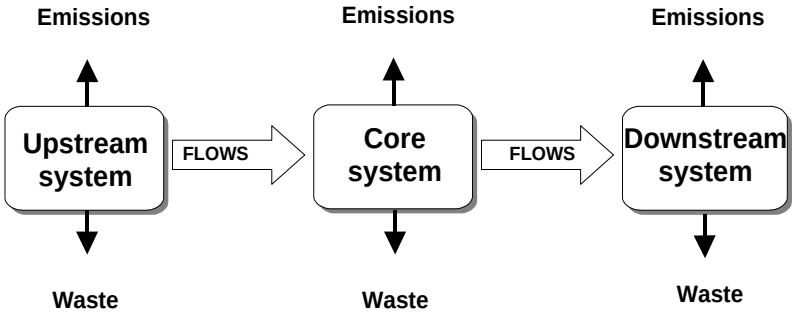

Figure 4.1 Life cycle assessment in ORWARE takes into account core system as well as the upstream and downstream systems. (cf. Björklund & Bjuggren, 1998)

In ORWARE up-stream material flows, associated with the use of energy carriers in the core system, are included. In a similar way, down-stream flows associated with the spreading of organic fertiliser from biological treatment or biogas utilisation may be included in the analysis. The core processes cause emissions in a defined area while upstream and downstream processes may cause emissions at undefined locations.

4.2.3 Functional Units

Another aspect of the LCA perspective in ORWARE is the use of functional units. In the ISO standard (ISO, 1997) a functional unit is defined as "the quantified performance of a product". It is thus a measure of the function a product (or a system) is able to fulfil, and is important to define clearly in comparisons of different systems. The main function of a waste management system is to treat a certain amount of waste from the defined area. Other functions, e.g. providing different kinds of products that can be recovered from waste, are also possible. Today, many waste management systems provide energy supply in addition to waste treatment. In other cases, it provides fertiliser, or in most recent years recycled products or materials. In order to achieve a just comparison between different waste management alternatives, functions not present in a certain system have to be compensated for. The compensation of functional units in ORWARE is achieved by expanding the system boundaries to include different so called compensatory processes (Figure 4.2).

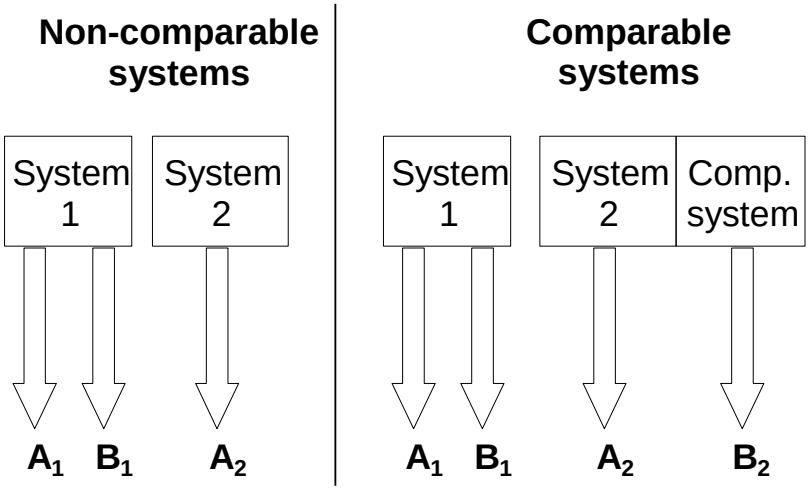

Figure 4.2 By expanding the analysis in Life Cycle Assessment with a compensatory system, the comparison of different systems can be made more just (Finnveden, 1998).

Compensatory processes also have up-stream and down-stream processes. Therefore, each treatment alternative in ORWARE has its own unique design of core system as well as different compensatory systems. This has been illustrated in Figure 4.3.

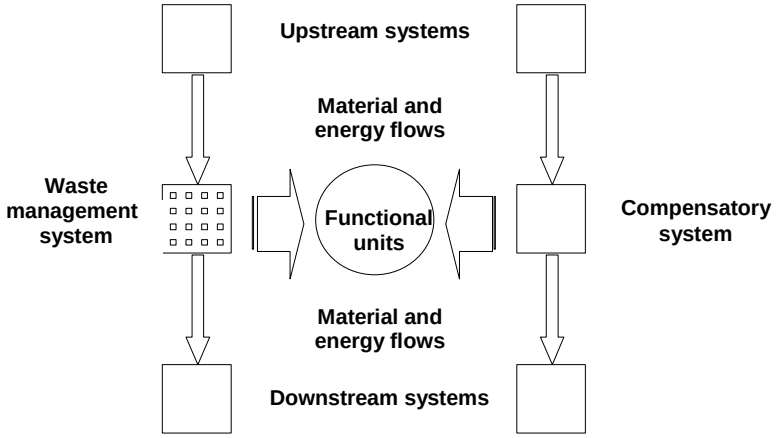

Figure 4.3 Conceptual model of the total system in ORWARE (Eriksson & Frostell, 2000).

The total system comprises the waste management core system, the compensatory system and their related up-stream and down-stream systems. The compensatory system, up-stream and down-stream systems constitute the enlarged system in ORWARE. Either the waste management system or the compensatory system provides the functional units.

4.3 THE ORWARE APPROACH AS A BASIS FOR TECHNOLOGY ASSESSMENT

The driving force of technical inventions has been to improve the quality of life. But well before the concept of sustainable development was coined in the growth-development discussions, the negative impacts of technology were recognised. Hence a variety of methods have been developed for evaluating the impacts of technical processes and products on a number of aspects of human wellbeing and the environment. An approach with a very broad scope is Technology Assessment (TA). One institution that contributed to the early development of TA was the U.S. Congressional Office of Technology Assessment (OTA). It was founded in 1972 to study technology change, with the purpose to provide early indications of the probable beneficial and adverse impacts of the applications of technology.

Technology Assessment (TA) is broadly defined by the United Nations Environmental Program as "a category of policy studies, intended to provide decision-makers with information about the possible impacts and consequences of a new technology or a significant change in an old technology. It is concerned with both direct and indirect or secondary consequences, both benefits and disadvantages, and with mapping the uncertainties involved in any government or private use or transfer of a technology. TA provides decision-makers with an ordered set of analysed policy options, and an understanding of their implications for the economy, the environment and the social, political and legal processes and institutions of society" (CEFIC, 1997).

Attempts have been made to categorise TA into different types. The Institute for Technology Assessment and Systems Analysis (ITAS) in Karlsruhe distinguishes between three types of TA with different starting points: project-induced, problem-induced and technology-induced TA (Berg, 1994). On the other hand four types of TA can be identified: awareness, strategic, constructive, and back casting, all of which may aim at either analysis or intervention (van Den Ende et al, 1998). The extent of issues covered in TA naturally requires that a range of tools be applied. In the case of UNEP's Environmental Technology Assessment (EnTA) environmental management tools such as Environmental Impact Assessment (EIA), Life Cycle Assessment (LCA), and Risk Assessment (RA) are considered by UNEP to be similar but separate from TA (UNEP, 2001). A relatively structured picture of how different tools and methods called "Instruments of TA" relate to each other is given (Ludwig, 1997). These "Instruments of TA" include EIA, LCA, environmental management and audit scheme (EMAS), and ecobalance (EB).

Recent discussions in the research group using ORWARE for LCA of MSW have led to predict its use as a tool that can contribute to the development and practice of mainly environmentally focused TA. As mentioned earlier technology assessment is mainly about introduction of new technologies into the market. There are many technologies that can be used for different applications. Waste management systems are one of the human made systems that share different technologies primarily designed and developed for other systems. ORWARE to begin with is applied in TA of waste management technologies.

There is a need to check for the effects of introduction of new technologies. This effect can be both positive and negative. Traditionally the checks for such effects are related to cost benefit analyses and political relevance. But effects of such type have to do with things other than mere cost benefit analyses and political orientation. The environmental, social and economic consequences should be taken into consideration in our quest for sustainable development. New technologies should be subjected for assessments that provide forum for looking into these equally contributing dimensions of influence on the society.

There is no hard and clear-cut rule on how these technology assessments are and can be done. Needless to say, however, the need for a simplified and structured analysis of different parameters that lies behind the environmental, economic and social implications of technologies is beyond doubt required. ORWARE aims in the long term at assessing these three arms of influence. The society at large and decision makers in particular should be informed about the performance of technological systems that are either totally newly introduced to the technosphere or used for the first time in new application areas.

More often conventional technology assessments are accompanied by vast qualitative analyses of different aspects of a technology that often end up in thick documents that contain different inputs from sectors of the

society that influence and can be influenced by the new technology. The process of compiling this information is time consuming. The TA documents are deemed to be of less practical significance due to the lack for simplification and structured methodology. Its features are characterised by 1) material and substance flow modelling of the technology system, 2) life cycle perspective, and 3) quantification of potential environmental and economic impacts gives it good quality in this regard.

Carrying out technology assessments with the possibility of dealing with enlarged boundaries is of great benefit. The LCA in ORWARE provided this flexibility of enlarging system boundaries to the extent of considering cradle-to-grave assessment of each and every input to the technological chain under analysis. Quantification has the potential of aiding and simplifying decision making. ORWARE is where both natural science and social science meet in terms of data inputs and result presentations. Both the physical economy and financial economy are dealt with scenario construction and room for sensitivity analyses where the effect of changing key parameters can be easily examined. An important feature is also the graphical model implementation, which provides an intuitive picture of the modelled system. If generalised, these basic principles offer the generic structure of a tool for system identification and analysis of potential impacts of other technology systems in TA with environmental focus.

For more information on TA and the coupling to the ORWARE approach see Assefa et al, 2001.

4.4 METHODOLOGICAL APPROACH IN THIS STUDY

The Life Cycle Assessment performed in this sub project was strongly dependent on findings in the main project, where gasification and catalytic combustion were studied from a technical point of view (Järås, 2001). The connection between this sub project and the main project was accomplished by using emission and energy data from combustion tests and then using this information together with literature data as input data in a computer model (ORWARE; Eriksson et al., 2002). In this way it is possible to assess the environmental and financial performance of the technology relative to other technologies and process types.

5 CASE STUDY FEATURES

5.1 SCOPE

Inventory and modelling of the technical systems was made in the model ORWARE. A number of scenarios – described in more detail below - were then simulated and evaluated. The data inventory was made in close cooperation between the authors and other staff both at the department for chemical technology but also at TPS.

5.2 SCENARIO DESCRIPTIONS

In all scenarios the timeframe of the assessment is one year. In other words an annual amount of waste is taken as input to the system. The functions of the system are then to (1) treat the annual amount of waste which corresponds to 24 000 tonnes of industrial waste based pellets and (2) generate electrical power and district heating by energy recovery from waste. The amount of electricity and district heating is defined by the system itself as the maximum amount generated in any of the simulated scenarios.

The potential impacts on environment, energy and economy were however not delimited to this year as emissions from the landfill are of long term character (see further in Appendix 2). Also in common for all scenarios are that the collection of waste is not included as it will be the same for all scenarios. Transport distances are related to the municipality of Kil. Kil is just taken as a role municipality and has been chosen as there are plans for building a gasification plant in the municipality of Kil. Four different treatment scenarios have been studied (see also Figure 5.1):

1. Gasification with catalytic combustion
2. Gasification with flame combustion
3. Incineration and
4. Landfilling.

The first two scenarios were selected for a comparison of the new technology of catalytic combustion with the conventional flame combustion. Both scenarios have the same type of gasification process; the only difference was changed conditions for the gas turbine. Scenario 3 was chosen to include a modern approach to direct thermal treatment, namely incineration. Finally, landfilling was also included in one scenario. Since landfilling of combustible waste is forbidden by law from 2002 and landfilling of organic waste from 2005, waste being landfilled will have to be redirected to other treatments in many Swedish municipalities during the coming years. Scenario 4 was aimed at giving an illustration of the benefits of avoiding landfilling.

5.2.1 Scenario 1 Gasification with catalytic combustion

As depicted in Figure 5.1 the first scenario begins with producing pellets from the waste at Frykenpellets in Kil. By pelletising the waste the water content is decreased and the drying procedure consumes heat and electricity. This must be done since the gasifyer demands for a homogenous fuel with high quality. The next step is the gasification process and then catalytic combustion of the product gas in a gas turbine. The process generates district heating and electrical power. Ash and slag is transported to a landfill site nearby.

5.2.2 Scenario 2 Gasification with flame combustion

This scenario is equal to scenario 1 except for the combustion technology used in the gas turbine. In this scenario a conventional gas turbine with flame combustion is used.

5.2.3 Scenario 3 Incineration

In this scenario waste is transported to Heden incineration plant in Karlstad 30 km from Kil by truck without being pelletised first. Then the waste is being incinerated and district heating and electrical power is generated. Ashes and slag are transported to a landfill site nearby.

5.2.4 Scenario 4 Landfilling

In the landfilling scenario, the unpelletised waste is transported to a landfill site 5 km from the point of collection. The landfill is equipped with a gas collection system and electrical power is generated in a gas engine that combusts the collected landfill gas.

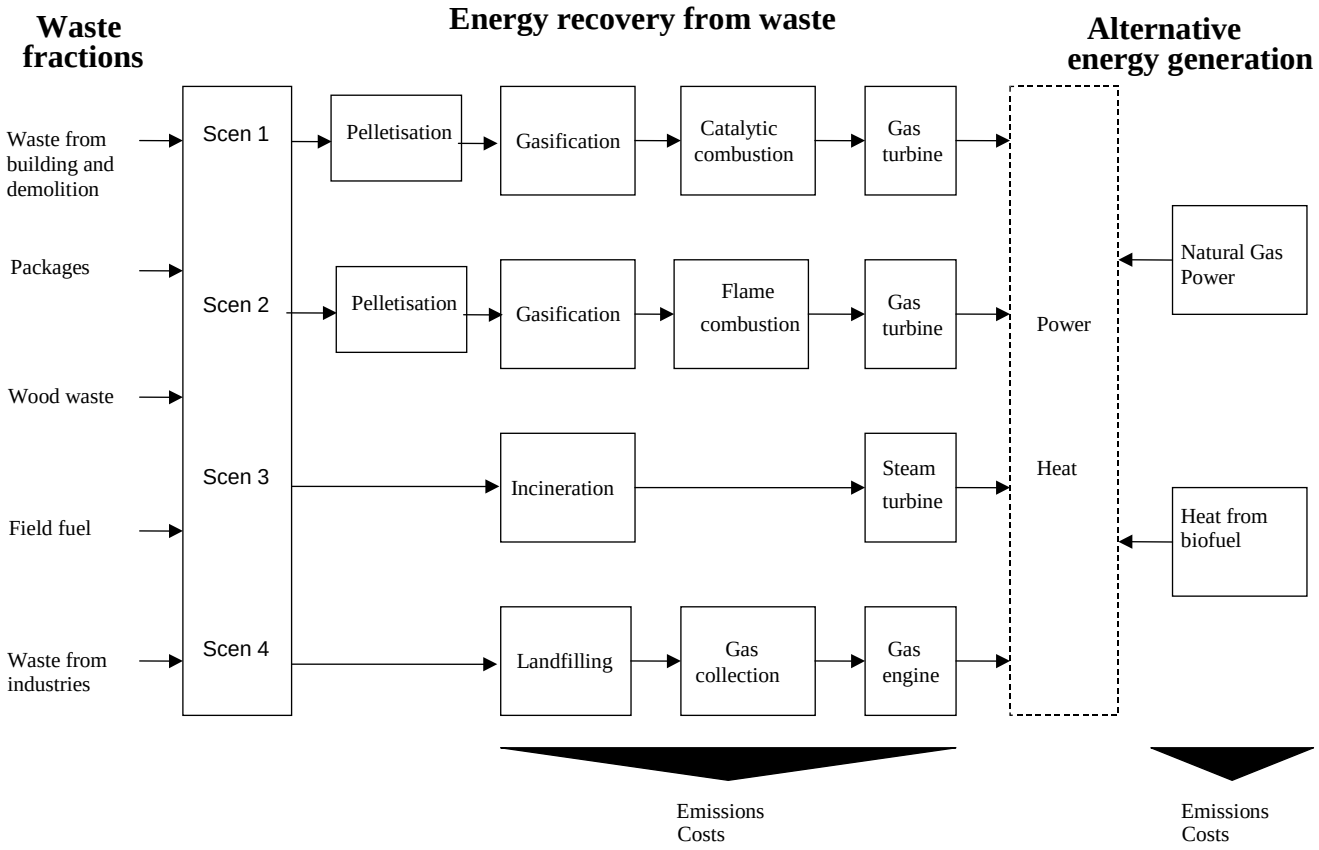

Figure 5.1 The main processes in the different scenarios.

In the study compensatory district heating is produced by combustion of biofuel. This assumption is a simplification since the real production system is much more complex and difficult to simulate. The power used for running the processes in the scenarios is supplied by the waste-to-energy technologies themselves while compensatory power is assumed to be produced from natural gas. This assumption is based on a marginal perspective on electricity and is recommended to use for evaluation of future systems (Weidema et al., 1999). Natural gas will probably due to CO_2 restrictions be the marginal power production in Sweden in the future.

5.3 ASSUMPTIONS AND DELIMITATIONS

The gasification is used in a combi cycle. It is not clear whether a combi cycle will be used when building a real plant but we have assumed so, since we believe that this is the most cost efficient and environmentally sound solution. Further, the future technologies in scenario 1 and 2 are assumed to be working properly, disregarding some of the problems encountered during the combustion tests. The composition of the industrial waste and the waste pellets were assumed to be the same.

Costs for gasification were based on pilot studies while costs for catalytic combustion were assumed to be the same as those for flame combustion with an additional cost for catalyst. The flame combustion used for estimating the costs and NO_X emissions are from a pressurised gasification plant in the city of Värnamo, Sweden (Sydkraft, 2001). An assumption made, was that there is no emission differences between pressurized and atmospheric gasification processes since the gasification process modelled was a TPS atmospheric gasification. For incineration and landfilling cost estimates for Swedish conditions were found in the literature (Björklund, 1998).

5.4 IMPACT ASSESSMENT

The emissions from the system studied were classified and characterised using methodology from Life Cycle Assessment (ISO, 1997 and Uppenberg & Lindfors, 1999) into the following environmental impact categories:

- Global Warming Potential, also called the green house effect
- Acidification Potential
- Eutrophication Potential
- Formation of Photochemical Oxidants
- NO_X - emissions

Other impact categories according to standardised Life Cycle Assessments such as human health, biodiversity etc. were not included. This was because there was no possibility to obtain relevant data for these impact categories within the scope and budget of this project. These problems were in line with experience from other ORWARE studies (Sundqvist et al., 2002). In addition to the environmental impact categories above, extraction of primary energy carriers, financial costs and environmental costs by valuation of emissions were assessed. Financial costs were penetrated in depth and revenues from purchase of district heating and electricity were included. The emission data was aggregated using a monetary valuation method (Finnveden et al., 2000). No evaluation of resource use was performed.

6 RESULTS

In a normal LCA the results are displayed for production of the functional unit. In a systems analysis of this kind there are several functional units simultaneously. How should the results be presented in this case? In previous ORWARE case studies the total annual impact has been chosen for comparisons. But since the study is a technology assessment study, we have chosen to show the environmental and economic pros and cons per unit of service delivered by each scenario. This means that in all diagrams results have been normalised with the net electricity production in each scenario. This makes the comparison unfair since the heat production from the different alternatives differs and is not accounted for. But the main reason to build a gasification plant would be to produce electricity which makes the environmental performance of such power production vital as a basis for comparison. The heat production is taken into account but is "emission-free" in this regard. For the sake of completeness the total annual impacts are displayed in separate diagrams in chapter 10 for a more complete comparison.

In the diagrams the emissions from the landfill during the first century is included and the emissions during remaining time is left out. That is why landfill is noted as "Landfill st" (Landfill surveyable time). In each scenario the energy generation amounts to 45 GWh as electrical power and 117 GWh as district heating. The energy flows in the different scenarios are summarised in Table 6.1.

Table 6.1 Energy generation in the scenarios. All figures in GWh.

Type of energy	Gasification with catalytic combustion	Gasification with flame combustion	Incineration	Landfilling
Electricity from pellets (netto)	45	45	28	15
Electricity from natural gas (netto)	0	0	17	30
Internal electricity consumption	11	11	2	0
Heat from pellets (netto)	79	79	117	0
Heat from biomass (netto)	38	38	0	117
Internal heat consumption	6	6	0	0

6.1 GLOBAL WARMING POTENTIAL

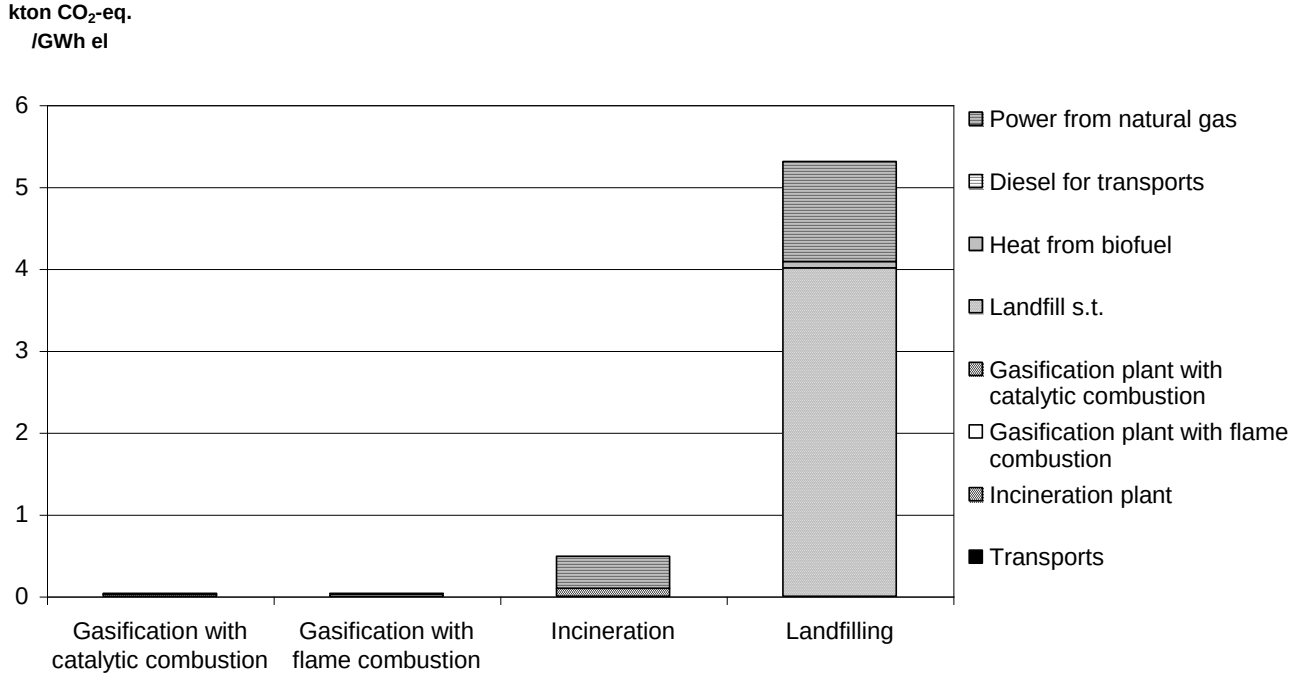

Figure 6.1 Global Warming Potential

The highest emissions of green house gases occur in the scenario Landfilling and the lowest contribution is found for the gasification scenarios. The largest impact in the landfilling scenario comes from the landfilling process where emissions of methane and laughing gas occur. A large contribution to GWP is also emissions from combustion of natural gas (fossil CO_2) for generation of compensatory electricity. For scenario Incineration emissions of CO_2 from natural gas (used for compensatory power production) is dominating but emissions of laughing gas from the incineration plant also give some contribution.

6.2 ACIDIFICATION POTENTIAL

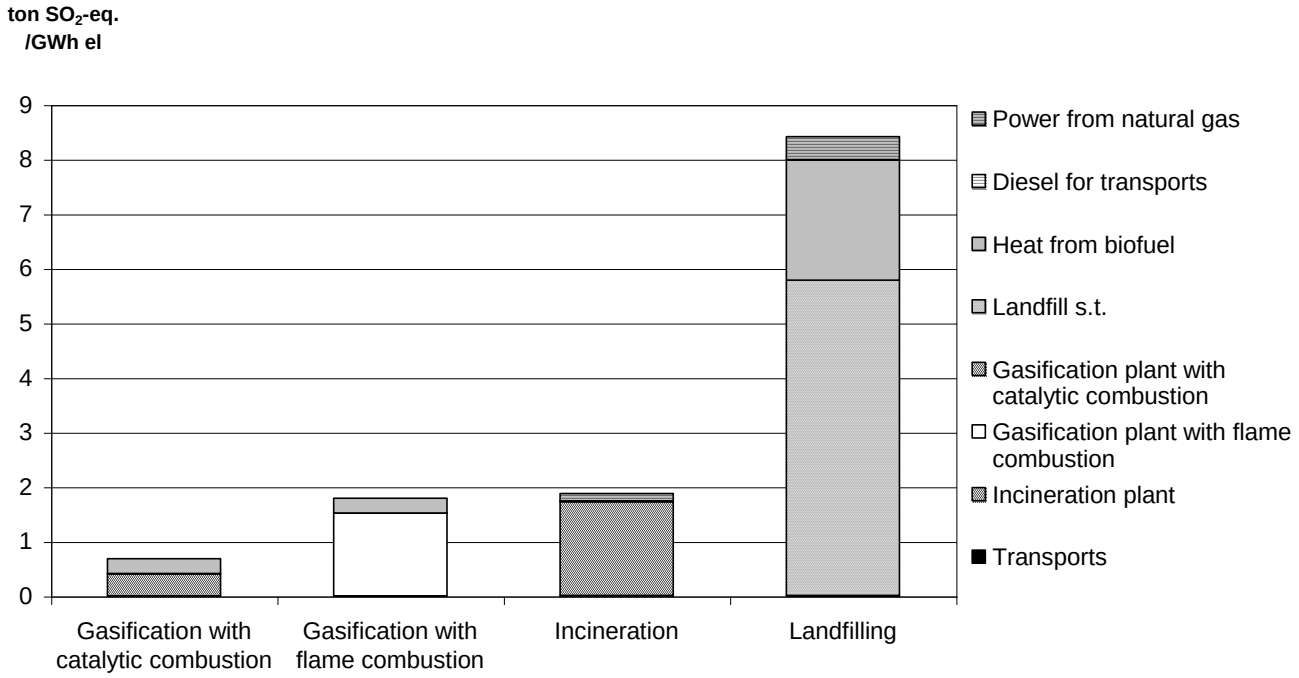

Figure 6.2 Acidification Potential

Scenario Landfilling is the main contributor to acidification. Scenario Incineration and scenario Gasification with flame combustion comes next and the lowest impact is found for scenario Gasification with catalytic combustion. In all scenarios the waste management processes have a higher impact than the compensatory processes. Compensatory heat and power amount to about 1/3 of the total impact for scenario Landfilling but much less for the other scenarios. There are high emissions of nitrogen oxides from the landfill site, emissions formed during the combustion of the collected landfill gas. Incineration of waste gives high emissions of ammonia compared to the other treatment alternatives. The contribution to acidification from nitrogen dioxide is similar for the incineration scenario and the scenario for gasification and catalytic combustion but emissions of sulphur dioxide are higher for incineration. Chlorine emissions also give a contribution to acidification in the incineration scenario, while there are no such emissions from the other scenarios. There is a big difference between the two gasification scenarios. With catalytic combustion the NO_X emissions are much lower than for flame combustion.

6.3 EUTROPHICATION POTENTIAL

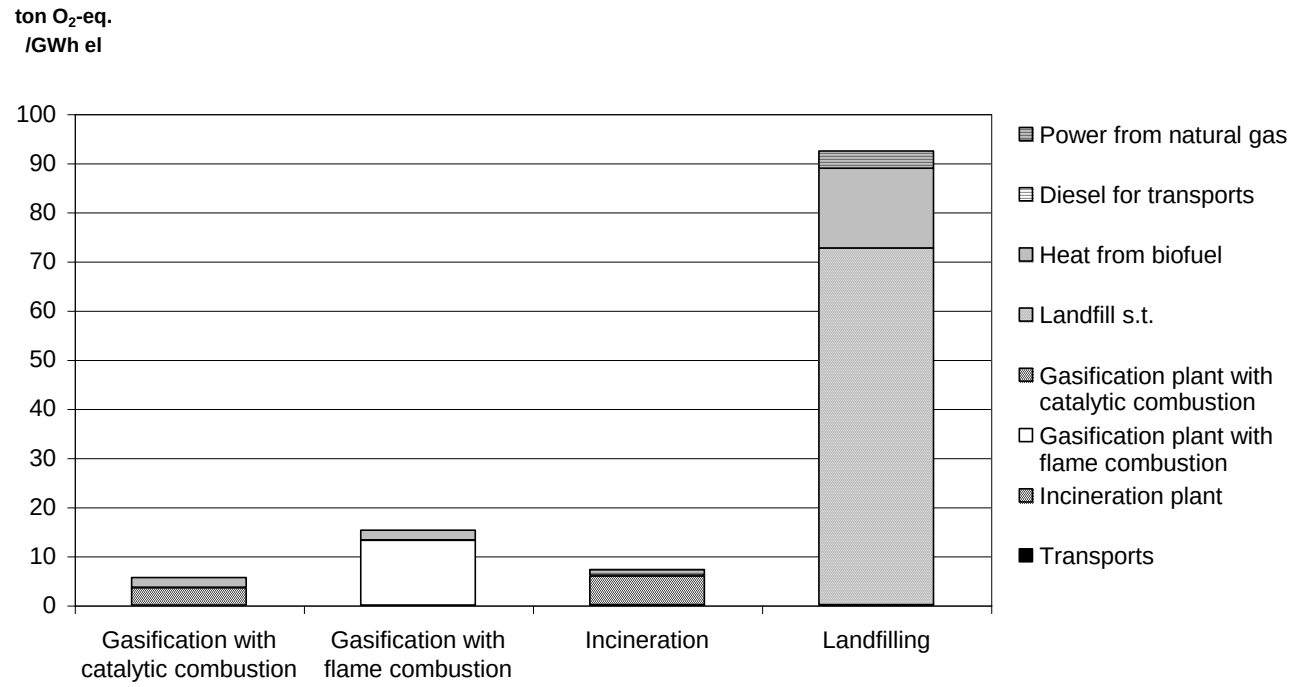

Figure 6.3 Eutrophication Potential

Scenario Landfilling gives the highest impact, high above the other alternatives. The lowest impact is found for scenarios Gasification with catalytic combustion and Incineration whereas scenario Gasification with flame combustion has about 3 times higher impact. The waste management processes are dominating over the compensatory processes in their contribution to eutrophication. The largest contribution from the landfilling process is emissions of nitrogen in the leachate and NO_X emissions from combustion of landfill gas. Emissions of NO_X are much higher in flame combustion, which result in a relatively high impact. Scenario Incineration has more or less the same impact as scenario Gasification with catalytic combustion. The small differences between these two come from somewhat higher NO_X emissions from the incineration plant and also some emissions of ammonia.

6.4 POTENTIAL FORMATION OF PHOTOCHEMICAL OXIDANTS

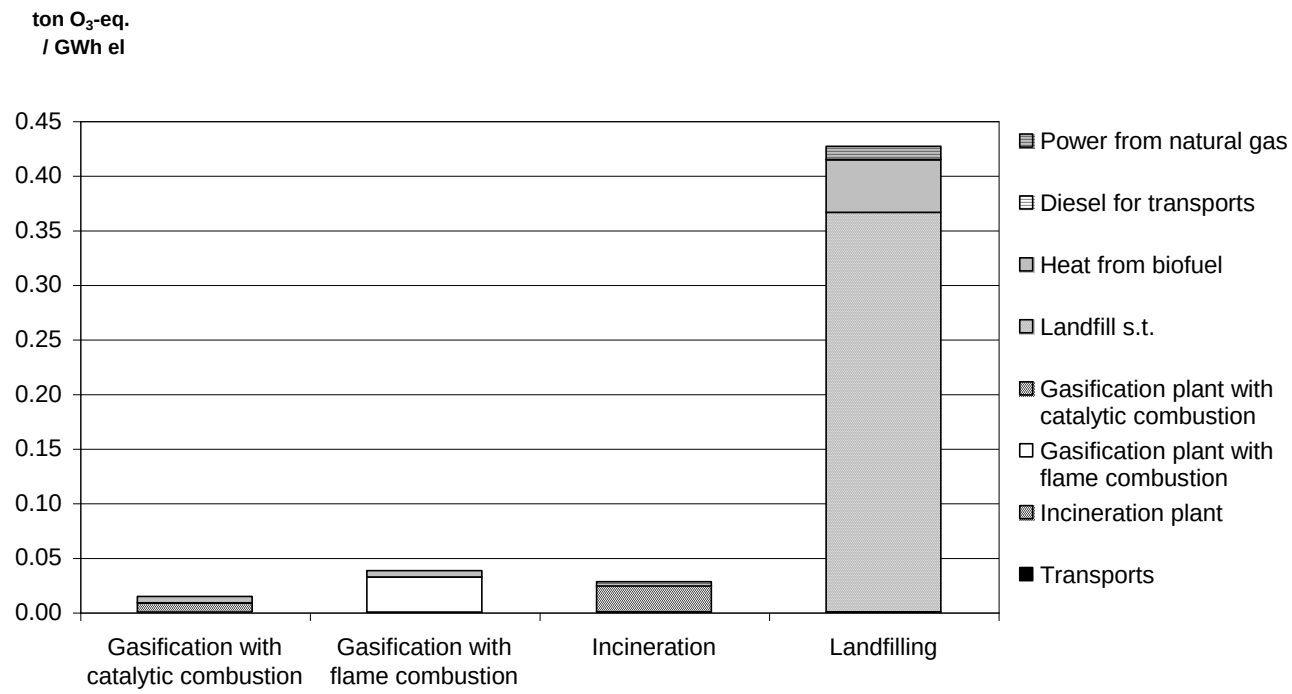

Figure 6.4 The potential formation of photochemical oxidants

The landfilling scenario gives the highest photoxidant production, much higher than the thermal treatment alternatives. Among them Gasification with flame combustion gives the highest contribution, next comes scenario Incineration and the lowest impact is found for scenario Gasification with catalytic combustion. In all scenarios emissions from the waste treatment processes dominate. Emissions of methane, VOC and NO_X are much higher from the landfill site than from the other treatment alternatives. The emissions come from the degradation processes in the landfill as well as from combustion of the landfill gas. In a comparison of the gasification alternatives and incineration the great differences are found for carbon monoxide and NO_X whereas catalytic combustion has the lowest emissions of CO, flame combustion a factor 3 higher and incineration still a factor 3 times higher emissions. In the case of NO_X, the incineration plant has approximately the same amount of emissions as catalytic combustion and flame combustion has three times higher emissions.

6.5 EMISSIONS OF NITROGEN OXIDES

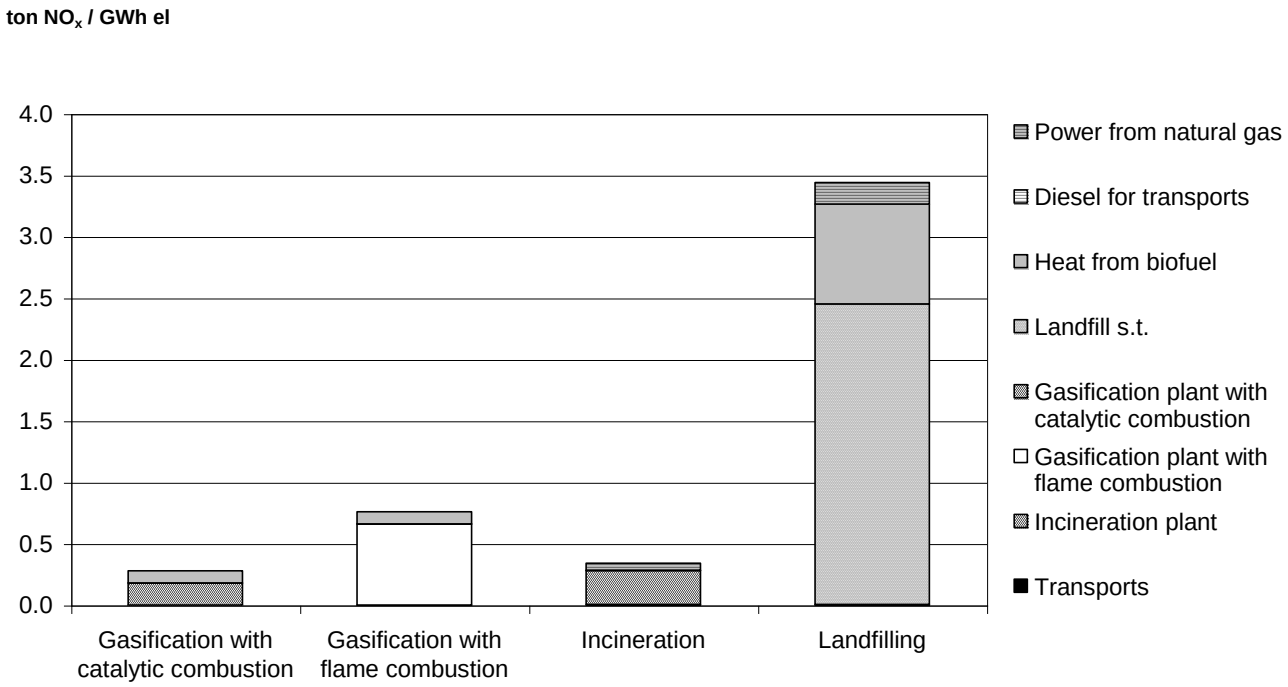

Figure 6.5 Emissions of nitrogen oxides

The diagram shows emissions and not environmental impact. The reason for including this diagram is that the largest benefit of the catalytic combustion technology is the reduction of NO_X. The picture indicates a large reduction of nitrogen dioxide for the catalytic combustion compared to flame combustion. The highest NO_X emissions come from landfilling when combusting the collected landfill gas. Compensatory heat and power production also give high NO_X emissions. The result is very similar to the diagram for eutrophication.

6.6 CONSUMPTION OF PRIMARY ENERGY CARRIERS

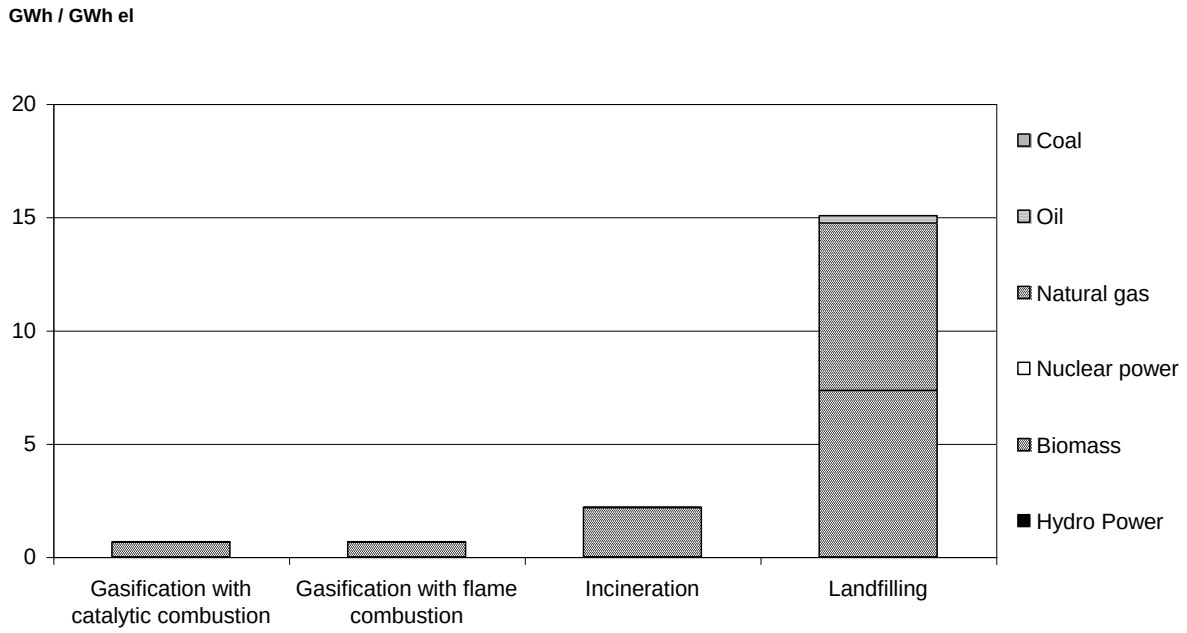

Figure 6.6 Consumption of primary energy carriers

As waste is landfilled, most of the energy in the waste is not recovered. That results in a consumption of biomass for compensatory heat and natural gas for power generation. Scenario Incineration fills the functional unit district heating by it self and there is only a consumption of natural gas for power generation. The gasification scenarios generate most electricity of all scenarios but some heat for drying of waste in the pelletising process as well as compensatory heat has to be produced from combustion of biomass.

6.7 FINANCIAL COSTS

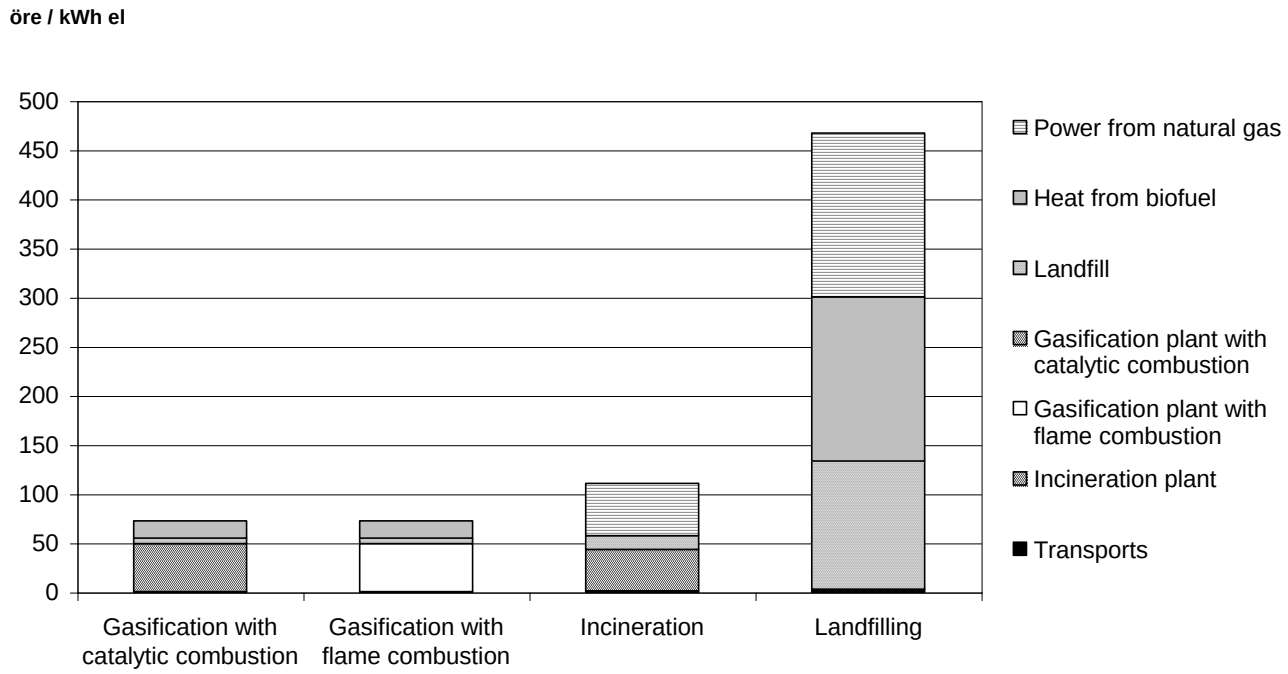

Figure 6.7.1 Total financial cost (1 SEK = 100 öre)

In Figure 6.7.1, the financial costs for the different scenarios have been illustrated. The cost is expressed as Swedish öre per kWh electricity produced in each scenario. Per unit electricity the gasification alternatives are the cheapest. Somewhat more expensive is incineration. In this comparison, the landfilling scenario becomes the most expensive. Landfilling produces very little electricity and all costs for the scenario have to be allocated to this small amount. In the thermal treatment scenarios the waste management costs dominate in each scenario, in scenario landfilling it is the other way around.

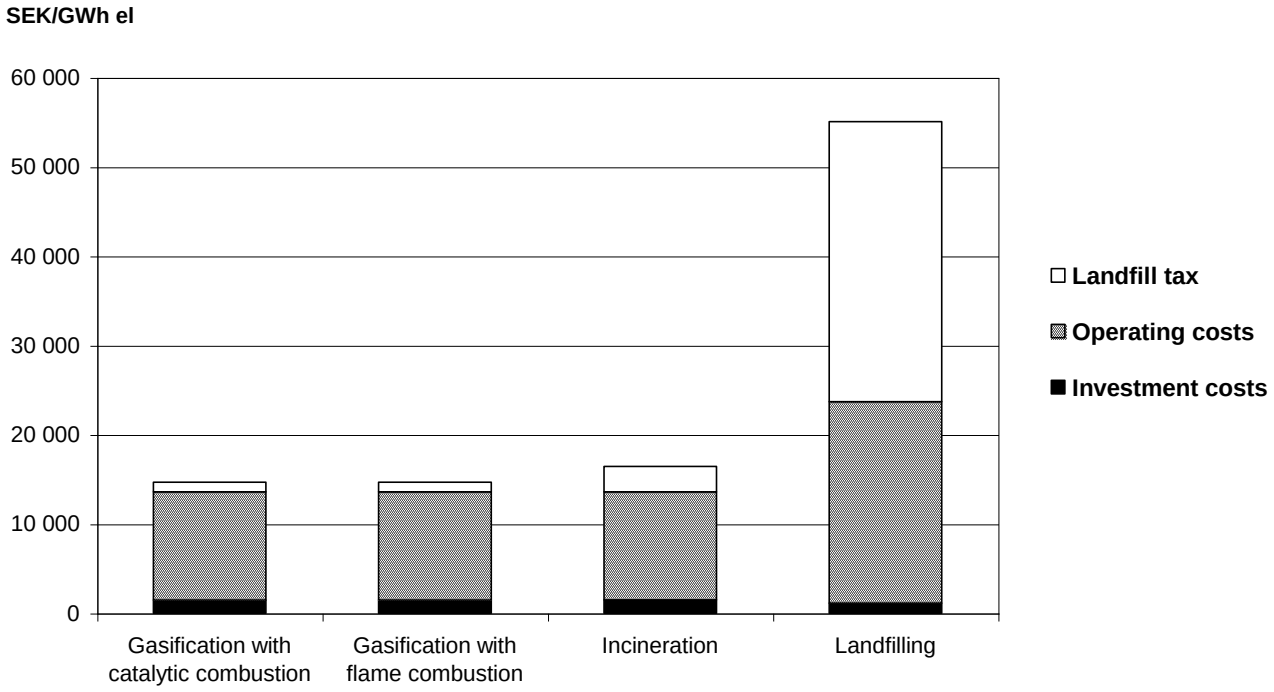

Figure 6.7.2 Financial costs for core system

In Figure 6.7.2 the financial costs for the waste management system is shown as the relation between investment costs, operating costs and landfill tax. Investment costs are low for all alternatives in relation to the other costs. Operating costs are almost half of the total costs for the landfilling scenario. That is explained by the low recovery of electricity, making the annual cost look high per unit electricity generated. It should be mentioned that costs for gasification are roughly estimated while costs for incineration and landfilling are based on experiences validated in other projects. Landfill tax is much higher in the landfilling scenario since the whole waste amount is disposed of in this scenario. In the other scenarios only slag and ashes are landfilled.

6.8 WELFARE COSTS

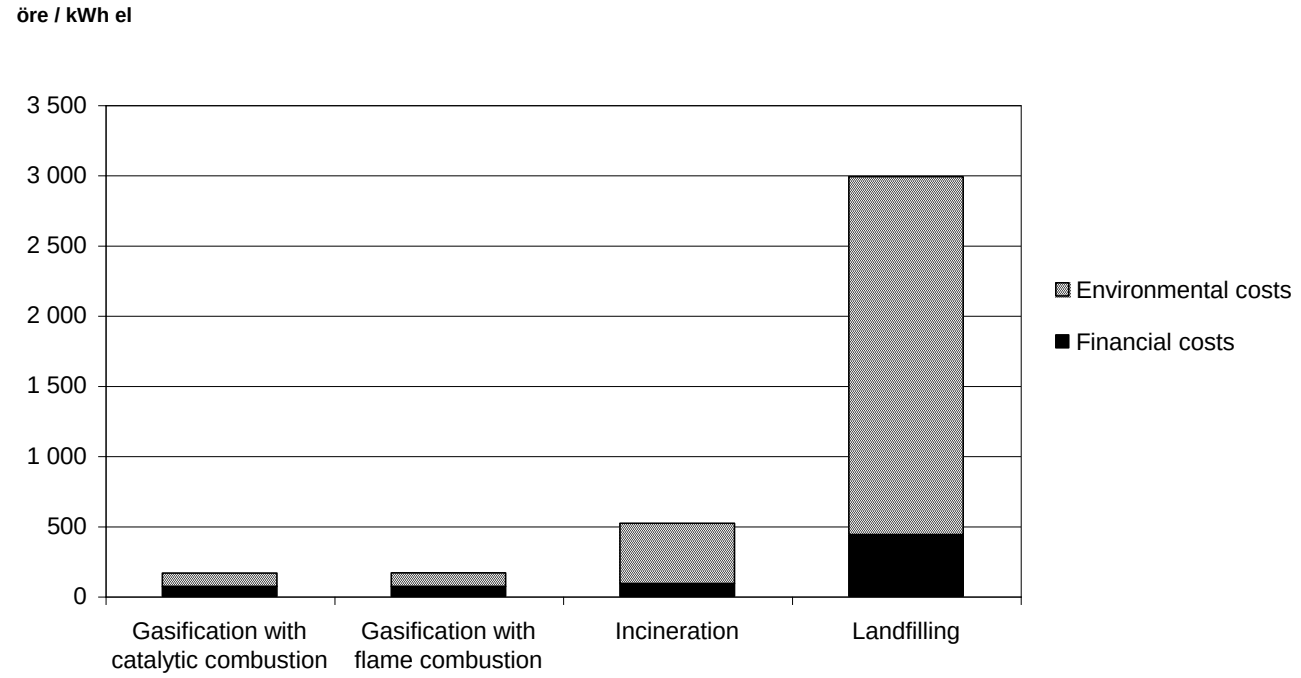

Figure 6.8.1 Welfare costs

Welfare costs are defined here as the sum of financial costs and environmental costs. The financial costs are more or less the same as in previous diagrams but a small reduction has been made for the environmental tax included in the diesel price, but the difference is extremely small. The environmental costs are the total costs according to a price valuation of the emissions from each scenario. The valuation method used is described in Chapter 11.

The highest cost is found for scenario Landfilling which is explained by the overall high emissions and low energy recovery in combination. Scenario Incineration has a cost of about 1/6 of the costs for scenario Landfilling. The gasification scenarios are the cheapest alternatives. The relation between the financial costs is described in the last picture. The environmental costs are highest for landfilling and least for gasification. In the landfilling scenario the largest contribution to the environmental costs comes from emissions of VOC in the landfilling process and from combustion of landfill methane in a gas engine. The environmental cost for the gasification scenarios comes mainly from the gasification process with emissions of Copper. The environmental cost for incineration is mainly from emissions of heavy metals such as Copper, Mercury and Chrome. The environmental costs are in principle equal for the gasification scenarios. When considering environmental cost for the emissions from the waste management system only, the environmental cost for flame combustion is almost twice as high as for catalytic combustion as emissions of NO_X and to a minor extent VOC are much higher.

6.9 OVERALL ASSESSMENT

To be able to compare the different alternatives/scenarios on a higher level, diagrams showing the relative impact for all considered impact categories have been made. In the diagrams, the results have been normalised with the results found for one of the scenarios. This means that every studied result parameter for that specific scenario has been set to "1" and the other scenarios in relation to this. A low value is better than a high one. In the diagrams one is given the impression that all impact categories are of the same relevance or importance. That is probably not the case, the reader has to judge which category is considered more vital than the other.

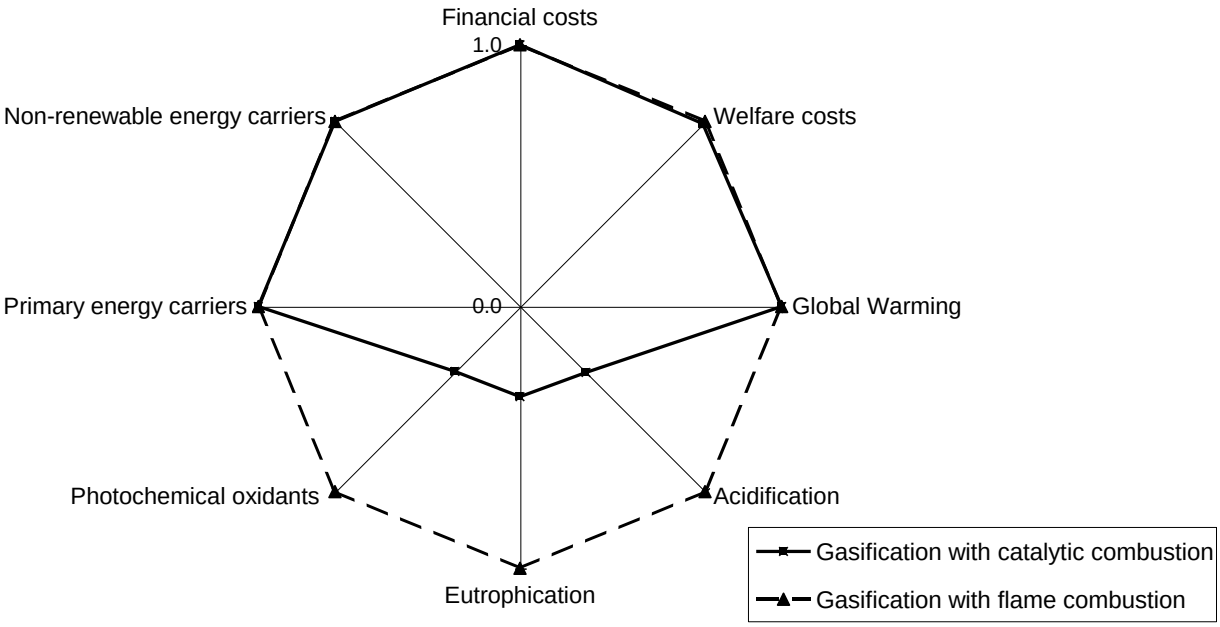

Figure 6.9.1 Gasification with flame combustion versus gasification with catalytic combustion

The results have been normalised with the results for gasification combined with flame combustion as a basis.

A comparison of the catalytic combustion and the flame combustion shows that all impact categories except acidification, eutrophication and photochemical oxidants remain the same. The gasification process is identical between the two alternatives; it is just the combustion technology in the gas turbine that is different. This explains why the fuel consumption and the costs are not changed (a minor extra investment is made for the catalyst but is not noticeable in comparison to the total impact). Emissions of greenhouse gases are also identical. For the other impact categories there are differences for several of the emissions involved in the impact assessment but NO_X is clearly the dominating one.

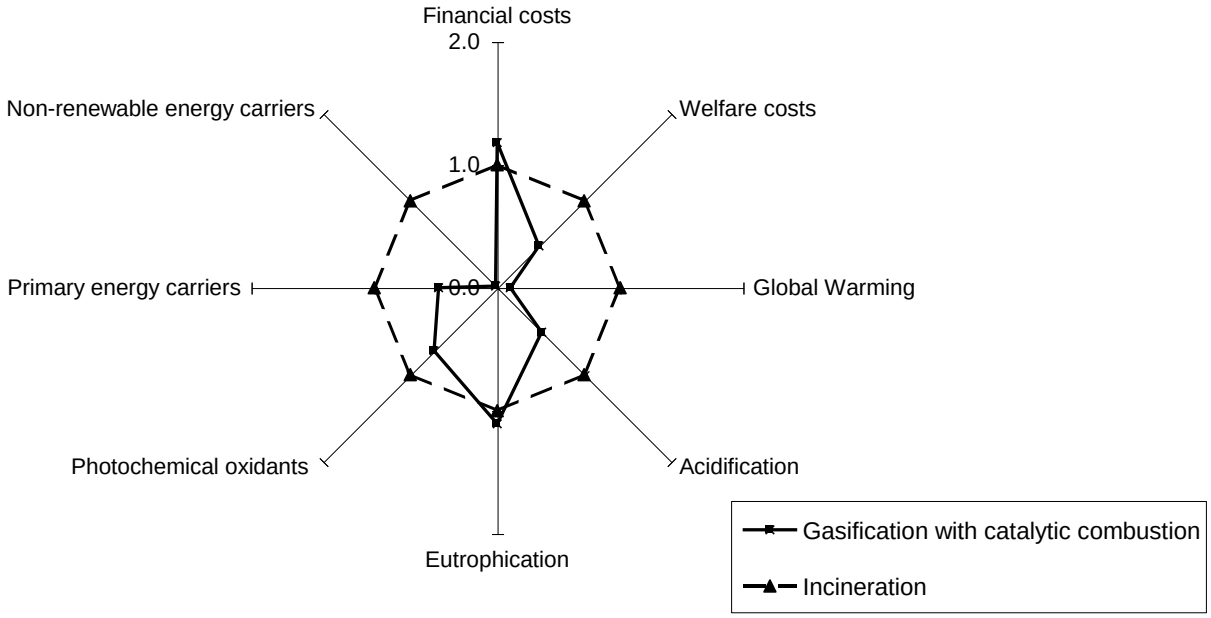

Figure 6.9.2 Gasification with catalytic combustion versus incineration

The results have been normalised with the results for incineration as a basis.

In this diagram it is clear that gasification with catalytic combustion is competitive to incineration. The small difference for eutrophication is within the error margin and is strongly dependent on the reduction of NO_X in the incineration plant. The explanation to this result is that a combi cycle in combination with natural gas as the alternative power generation is a better system solution than incineration with biofuel as compensatory fuel. This conclusion is based on the fact that almost the same picture as above can be seen when comparing flame combustion with incineration. It is identical except for the acidification, the eutrophication and the photochemical oxidants which are higher for flame combustion than for incineration. Financial costs are somewhat higher than for incineration but could also claimed to be within the error margin since the inventory of costs are more uncertain due to the fact that there is no plant with gasification and catalytic combustion in operation.

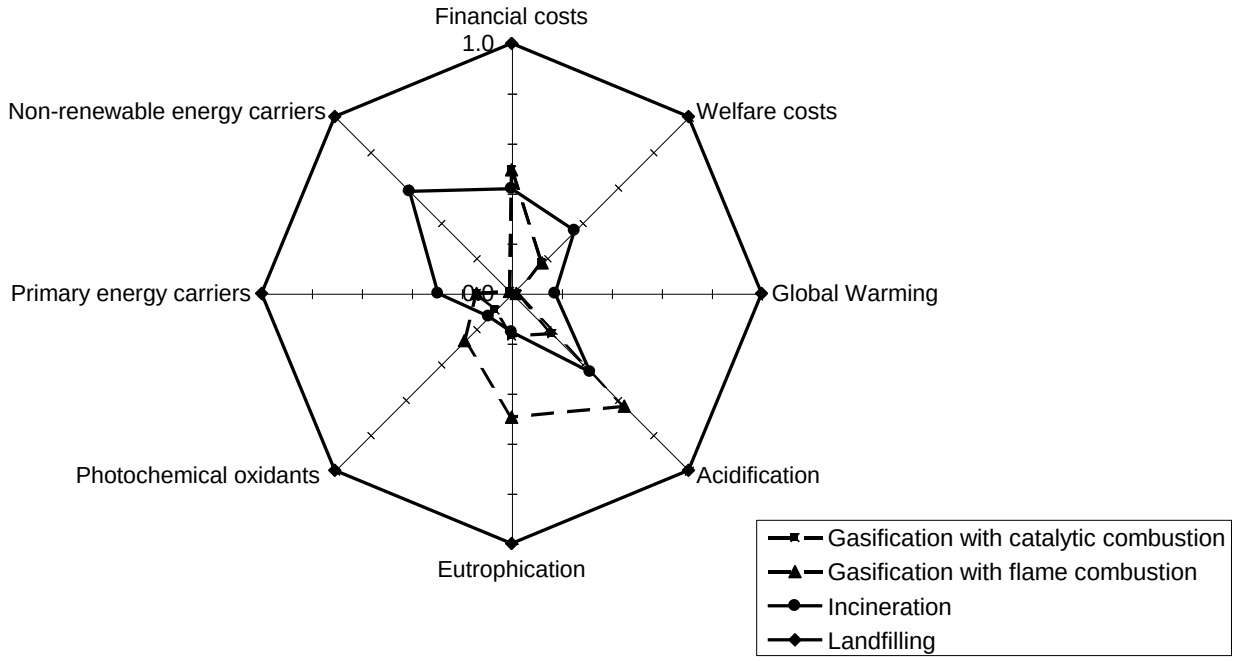

Figure 6.9.3 Thermal treatment (gasification and incineration) versus landfilling

The results have been normalised with the results for landfilling as a basis.

With respect to all impact categories considered, landfilling should be avoided in comparison to thermal treatment. The best environmental solution seems to be gasification with catalytic combustion. It is better in all impact categories except for financial costs. This shows that the environmental performance is not free of charge and the price is illustrated here in financial terms.

7 SENSITIVITY ANALYSIS

In studies of this kind, it is often of great interest to identify key assumptions or key parameters in the whole analysis and perform a sensitivity analysis to investigate the relative influence on the results from changes in the input parameters. This is in order to see if the result obtained is trustworthy. In this study two changes have been investigated. First a price sensitivity analysis was made where revenues from sold heat and power were altered for each scenario/treatment method. Higher energy prices are likely to be introduced in the future and thus it was of interest to investigate the sensitivity of the results to this phenomenon. The price sensitivity analysis was based on financial costs, but could be developed to include environmental costs as well, although it is not clear at the moment how to do this in a proper way.

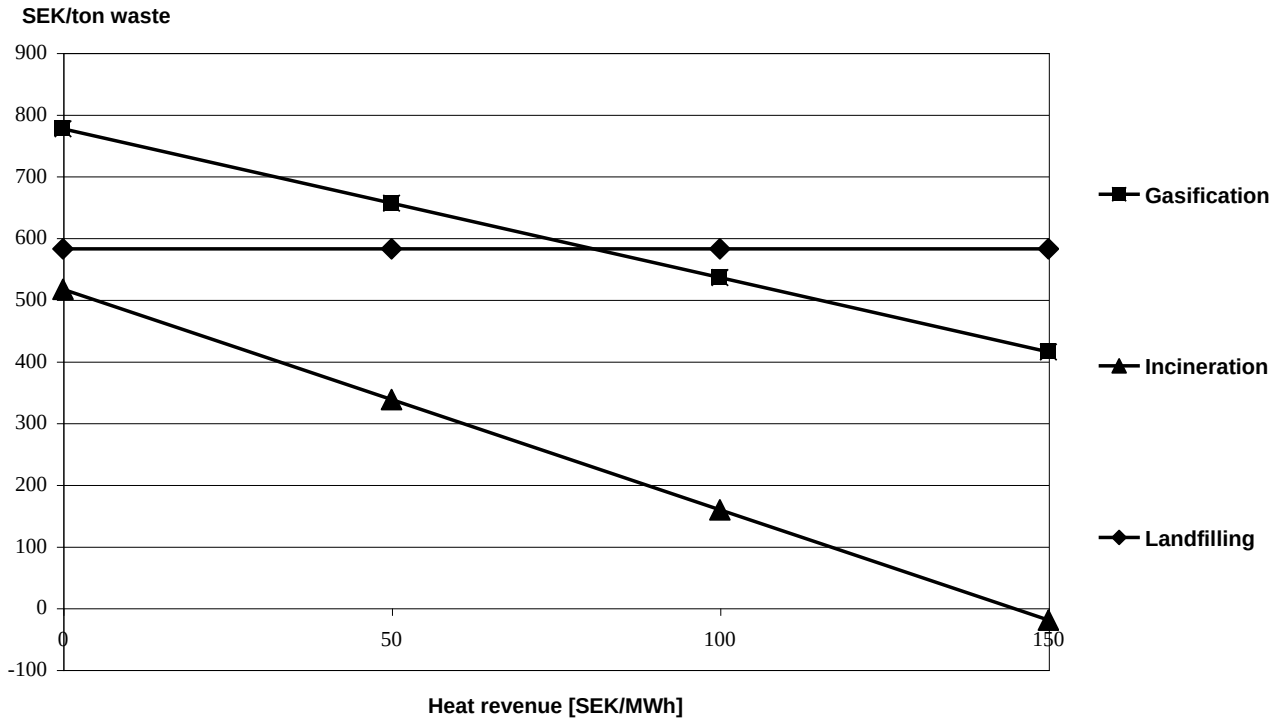

Figure 7.1 Changes in treatment cost when revenue from district heating is included

The diagram illustrates the relation between treatment cost per ton of waste and the revenue for district heating. There is no pricing for the electricity delivered. From the landfill, no heat is recovered which means that no cost reduction can be achieved. Incineration is profitable at a price just below 150 SEK/MWh. The treatment costs for the gasification scenarios become lower in the same way as for the incineration scenario, but since the investments costs are higher for gasification followed by combustion (flame or catalytic), the total cost is always higher than for incineration. The picture corresponds to the reality since neither landfilling nor gasification are processes designed for heat recovery.

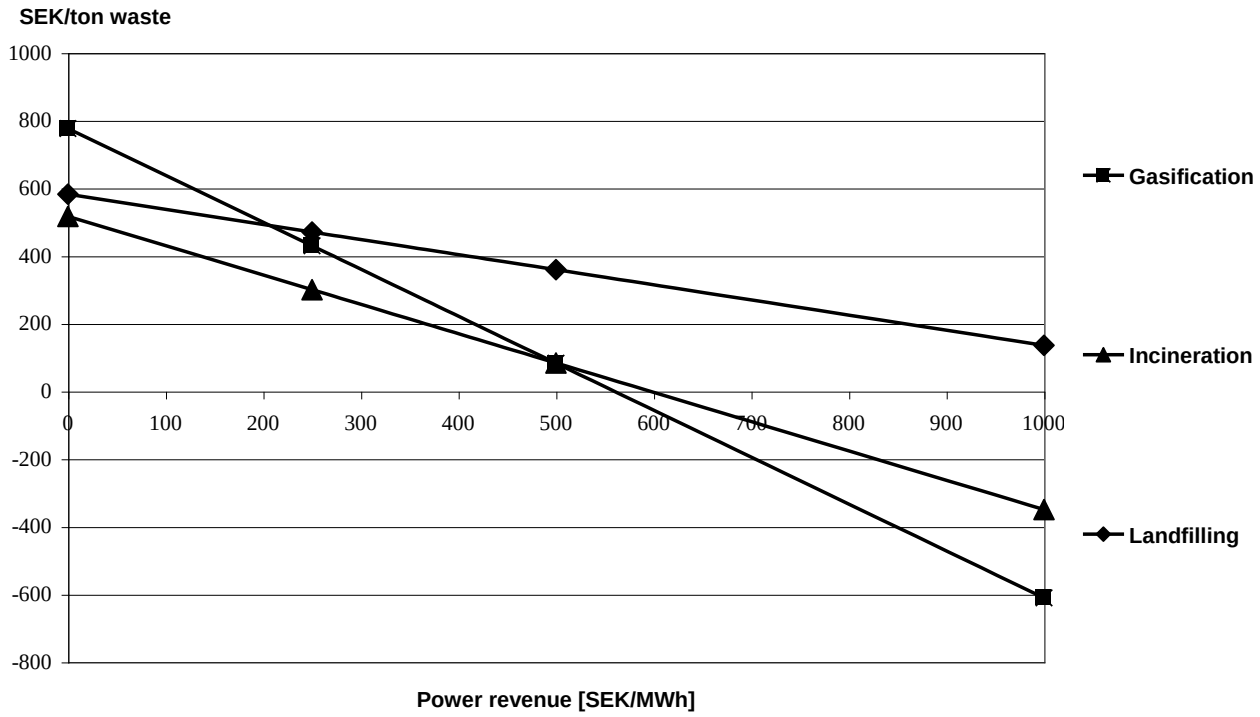

Figure 7.2 Changes in treatment cost when revenue from electricity is included

When the electricity is priced, the picture changes completely. All methods become cheaper and the one with the highest power production capacity changes the most. Incineration is profitable at a price of approximately 600 SEK/MWh (60 öre/kWh) and landfilling far beyond 1000 SEK/MWh (1 SEK/kWh). At a price of app. 200 SEK/MWh gasification becomes cheaper than landfilling and at around 550 it becomes profitable. To compete with incineration the price has to be some 500 SEK/MWh (50 öre/kWh).

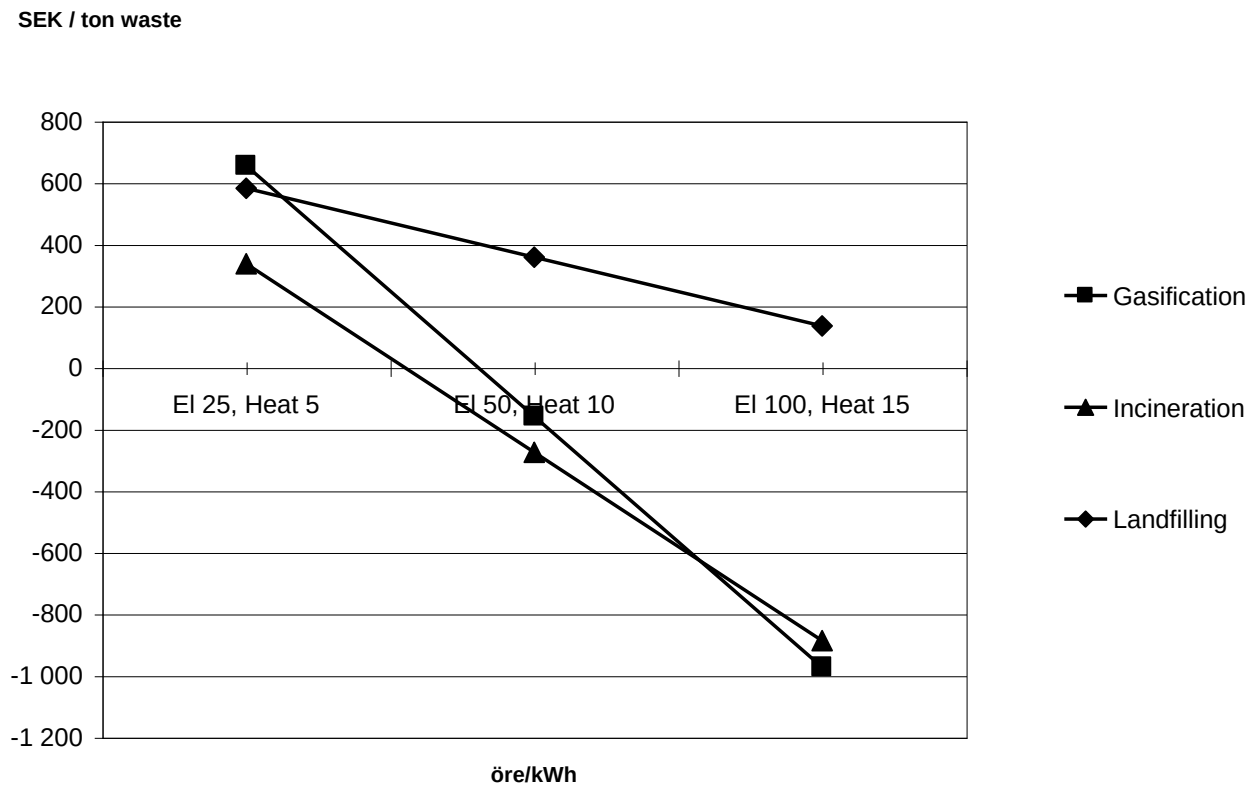

Figure 7.3 Changes in treatment cost when including revenues for district heating and electricity

In this diagram revenues for both electricity and district heating are included. The diagram illustrates three points with different prices for electrical power and district heating. The prices for electricity were 25, 50 and 100 öre/kWh and the corresponding heat prices were 5, 10 and 15 öre/kWh. It is of course impossible to predict the correlation between price for district heating and electricity but it illustrates the sensitivity of the system with respect to the two functional units. A doubling or halving of each price affects the system in this way.

The second sensitivity analysis deals with the management of the gasification residues. The rest products from gasification are new to the ORWARE analysis and are not easy to decide whether to treat them as slag or ash. Such a choice matters since it has also to do with environmental behaviour in the landfilling model. Currently the landfilling model can take care of ash and slag from incineration and it is unknown how the gasification rest product would behave in a landfilling due to the lack of knowledge concerning landfilling of such products. Considering this problem a sensitivity analysis has been done by considering the gasification residue to (1) behave as ash from incineration and (2) the slag from incineration. The difference between these two cases manifests in terms of environmental economy related to emissions to air, water and soil. The environmental costs in figure 6.8.1 show the second case where the residue is taken to the landfill as slag. The rank of the scenarios becomes different when it is treated as ash as shown in figure 7.4.

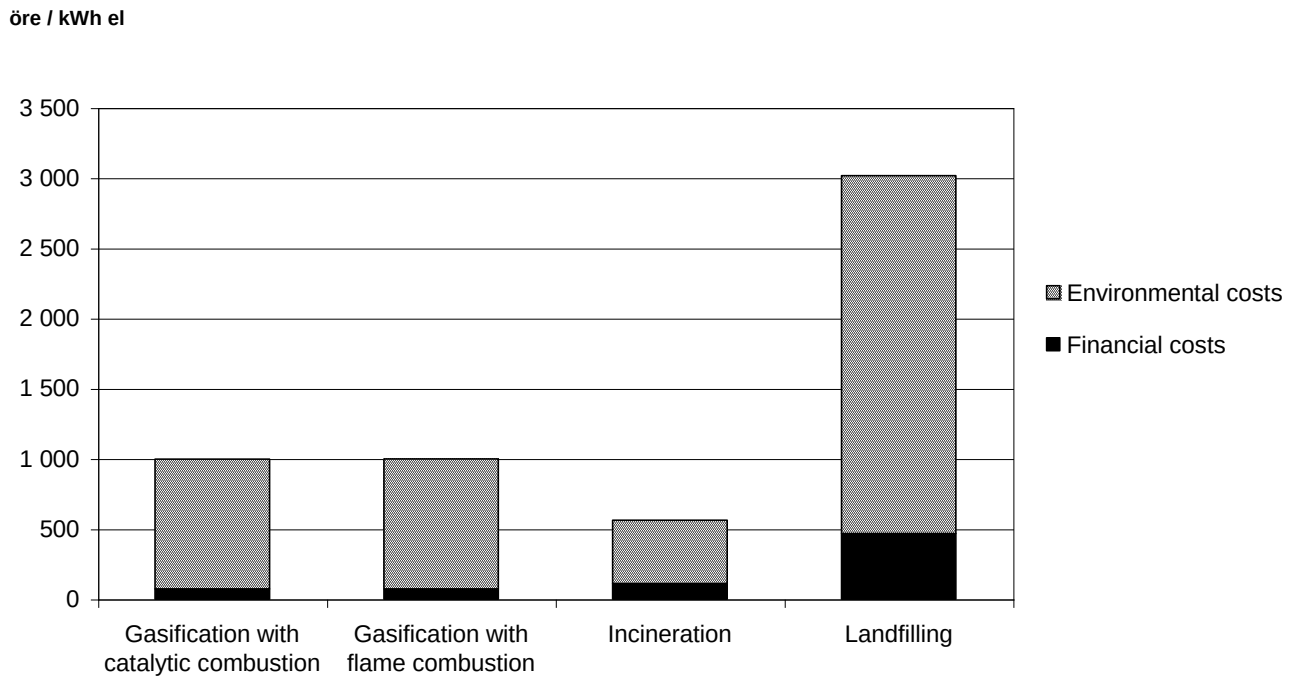

Figure 7.4 Welfare costs where residues from gasification is treated as ash

This change in the rank of scenarios is because of the heavy metals (mainly copper) contained in the residues. Heavy metals including copper behave differently when landfilled as ash or as slag according to the model. Much more copper is leached out as water effluent when the residue is landfilled as ash than when landfilled as slag.

8 DISCUSSION AND CONCLUSION

8.1 ON THE RESULTS

From the results presented in chapter 6.9 it is obvious that a decreased use of landfilling in favour of an increased energy recovery from waste is positive from all considered impact categories. Gasification with energy recovery in a combi cycle using catalytic combustion in the gas turbine is the most competitive technology from an environmental point of view. It is somewhat more expensive than incineration but has better environmental prestanda and may pay off in a shorter time if the price of electricity rises. This conclusion depends, however, on the assumption that the gasification and catalyst technologies work as the researchers presume and that the fuel is of high quality. For this, the pelletising unit is vital in the technology chain. The catalyst will probably not lead to any problems. It just has to be regenerated once a year. It is, however, possible to construct a catalyst with longer technical life-length, but due to the high cost involved it will probably be delimited to one year. This makes it possible to regenerate the catalyst as the plant is stopped for maintenance.

An important break-through for the catalyst technology may be expected when it is fully developed. The cost for the catalyst is supposed to be relatively small but the advantages in terms of decreased emissions of primarily NO_X are great. Advantages will be seen, both from an ecological and an economical point of view since there is a taxation system in Sweden that financially rewards plants with low emissions of NO_X. Some problems remain to be solved, e.g. handling of the gasification residue. This shows that a technology can not be considered sustainable until the total life cycle impact is decreased. It is beneficial that gasification is better than incineration during the operation phase, but this is of minor benefit if ashes and slag from gasification cause severe environmental problems in the future.

Another conclusion from this study is that it offers as a comparison of a combi cycle and a Rankine cycle and at the same time as a comparison between flame combustion and catalytic combustion. It was thus both a technology assessment and a system design assessment. To use gasification as a treatment method is more complex than incineration or landfilling but here it is possible to use a combi cycle. The overall efficiency may be somewhat lower than for incineration but the power production is relatively higher. Since the marginal production of electricity is more polluting than the alternative to waste incineration, namely combustion of biofuel, gasification is a more sound investment from an environmental point of view. The benefit of catalytic combustion compared to flame combustion is of course the low NO_X emissions, which affect eutrophication, acidification and formation of photochemical oxidants. A combination of a combi cycle and catalytic combustion will then of course be the most competitive one.

8.2 ON THE DEVELOPMENT OF THE TA METHODOLOGY

This is the third study where ORWARE has been used in a systems analysis aimed at a general technology assessment and not systems analysis of waste management. The previous ones were Assefa (2000) and Fahlstedt (2002). In all the three studies, waste has been used as a fuel for the thermal treatment processes, but more and more the systems analyses have taken the character of an analysis of an energy system rather than a waste management system. This is an interesting development and one of the many variants of future ORWARE applications that have been anticipated within the research team. In the first study there was a focus on transports and the links between waste management, energy recovery and the transport system. The second study introduced a new functional unit since also district cooling was produced from incineration besides electricity and district heating. The system design in Fahlstedt´s study emphasised a high overall efficiency. The system design in Assefa´s study emphasised a substitution of the most polluting activities (waste substitutes petrol in cars rather than biofuel in district heating). This study was more aimed at an examination of a coming technology. The data was more uncertain than in the previous studies and the real performance of technologies could not be very well documented in numbers.

There are important problems with this type of analysis. One of the more severe is to compare existing and non-existing full-scale technologies. Who knows how the catalytic concept will function when it is fully developed? With help of colleagues, good estimates can be made but nevertheless it is not the same as using data from existing facilities that are using a technology that has been developed during decades. Connected to this are problems in retrieving reliable data. There is no running waste gasification plant with catalytic combustion in Sweden and the gasification technologies differ between different plants. We have combined data from gasification of waste in Italy with those from pilot plants in Sweden using RDF and other fuels; and a natural gas catalytic combustion process developed by Catalytica in the US with an experimental catalytic combustion done in Sweden. There is also a fundamental difference between data uncertainty for emissions used in the calculations of ecological impact and financial data used for financial cost calculations. In the first case, emissions have at least been measured, even if they may be associated with great uncertainties. The financial costs for scenarios 1 and 2 were only estimated based on pilot studies.

An interesting methodological question is how the functional units are defined. Normally in this type of studies, as well as in this one, the functional units are defined by the system itself. Maybe one should consider basing them on the actual need of predominantly district heating in the municipality. It is not clear how this would affect the outcome of an analysis but if there is a difference between small or big plants in terms of flue gas cleaning and costs per functional unit, this type of considerations could be interesting. The division of costs between investment and operation could be altered in such a case.

8.3 FUTURE RESEARCH

Considering the results in this study, an important future research area is to test the impact of using an SCR in the flue gas cleaning system of the gasifyer. What would be the result if pressurised gasification was used instead of atmospheric? How should the gasification residues be taken care of? More of the recent research about the chemical composition and leachability of these residues would have to be put in and maybe also a brand new submodel in the landfill model, which would correspond to landfilling of gasification ashes. A more detailed analysis of the players (researchers, the municipality, the pelletising industry, the gasifying company etc) would also be of interest and also to study other applications for catalytic combustion.

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10 APPENDIX 1 ANNUAL RESULTS

10.1 GLOBAL WARMING POTENTIAL

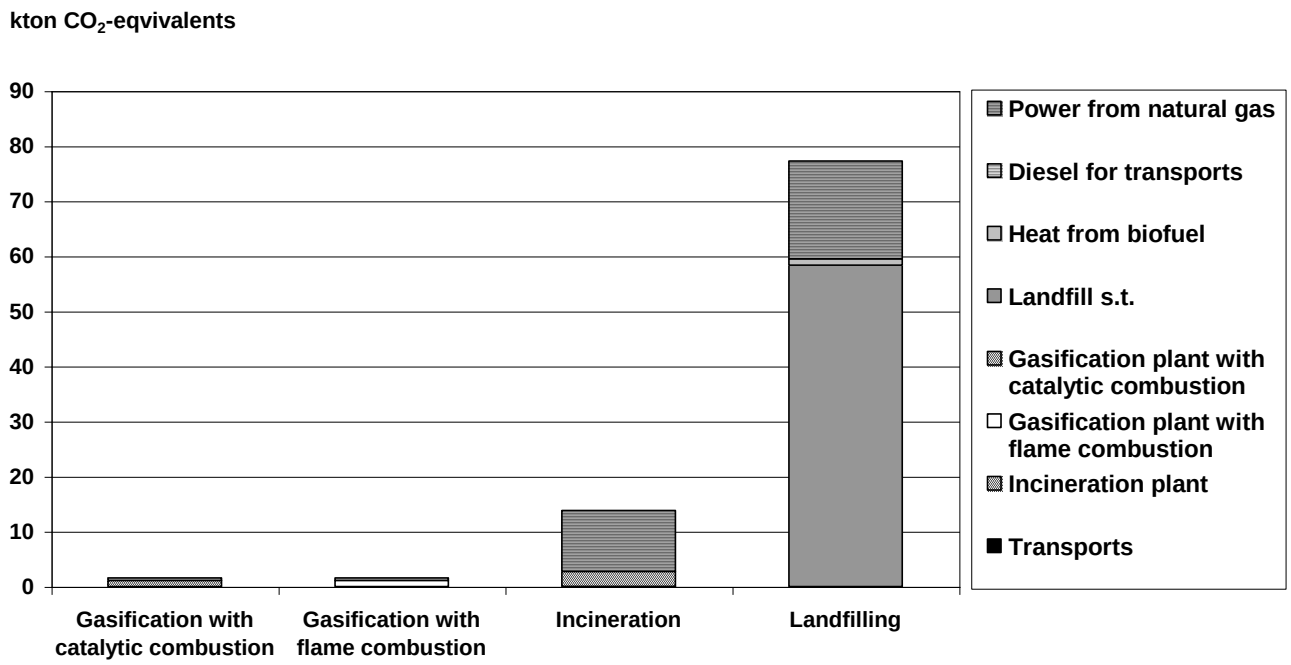

Figure 10.1 Global Warming Potential

10.2 ACIDIFICATION POTENTIAL

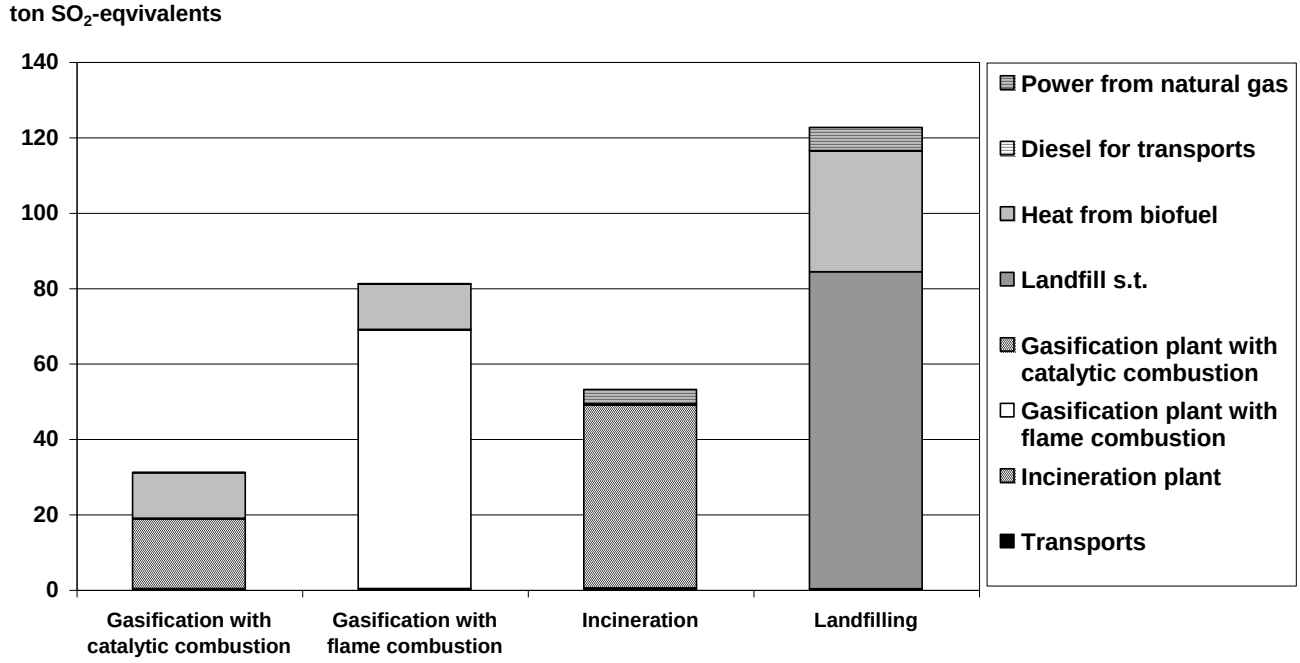

Figure 10.2 Acidification Potential

10.3 EUTROPHICATION POTENTIAL

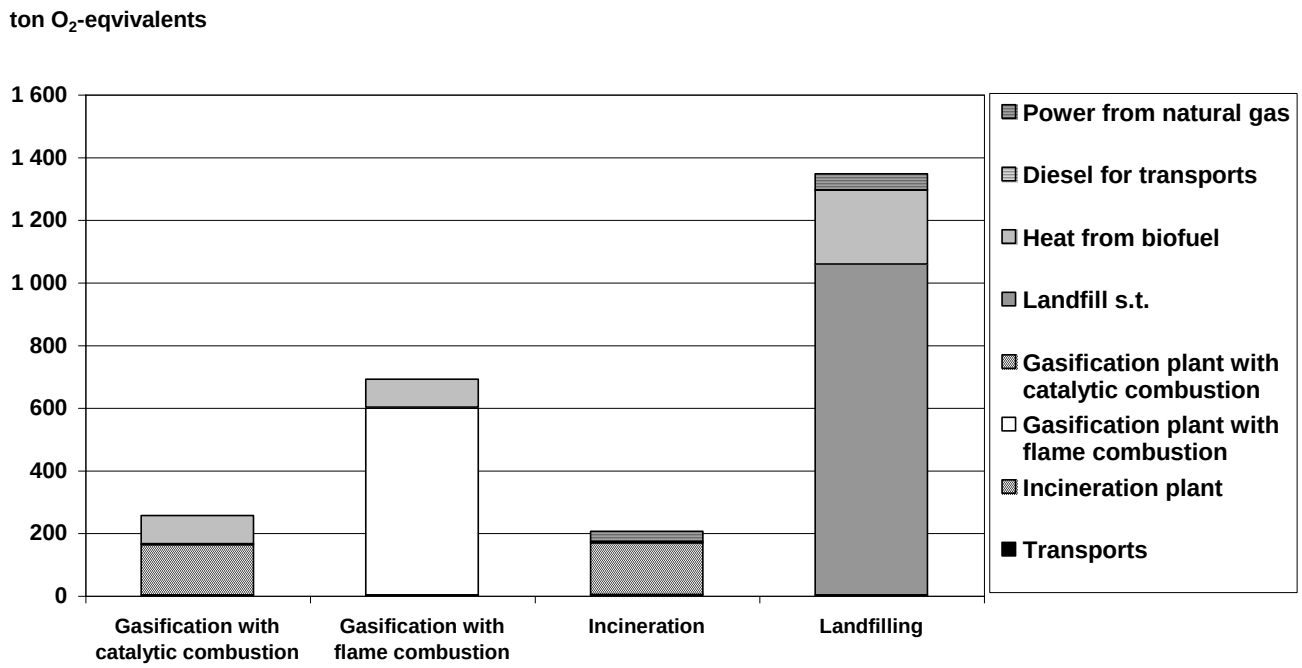

Figure 10.3 Eutrophication Potential

10.4 POTENTIAL FORMATION OF PHOTOCHEMICAL OXIDANTS

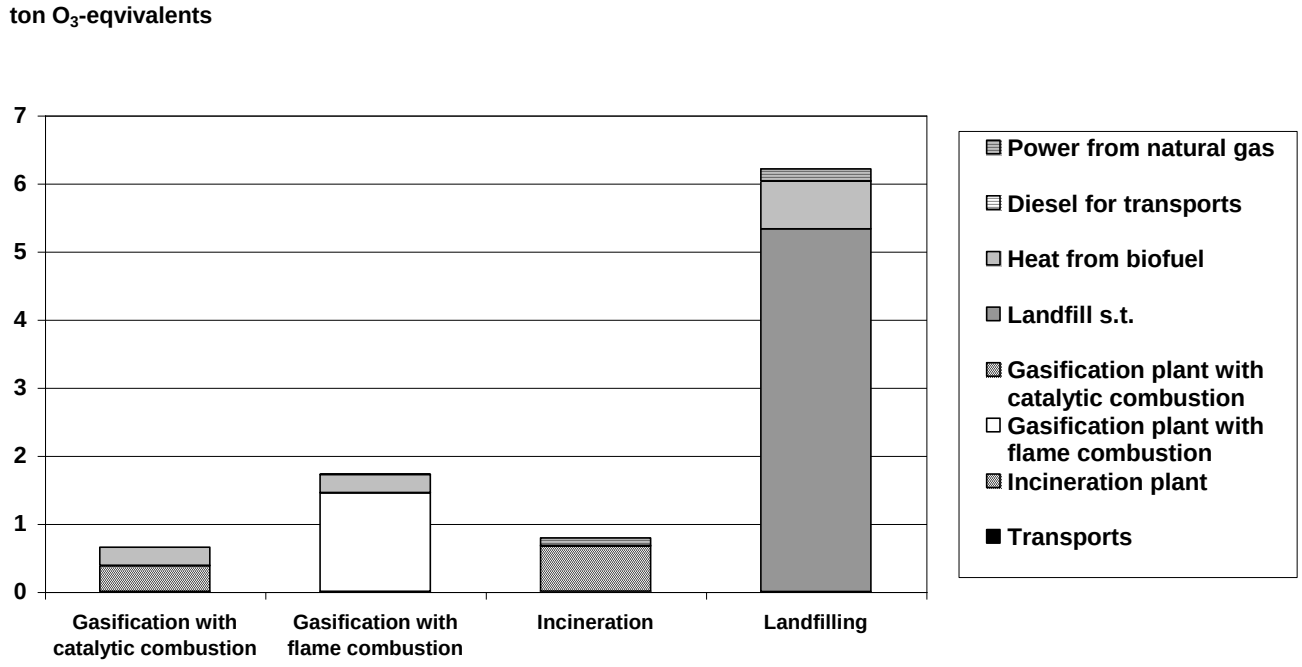

Figure 10.4 Formation of photochemical oxidants

10.5 EMISSIONS OF NITROGEN OXIDES

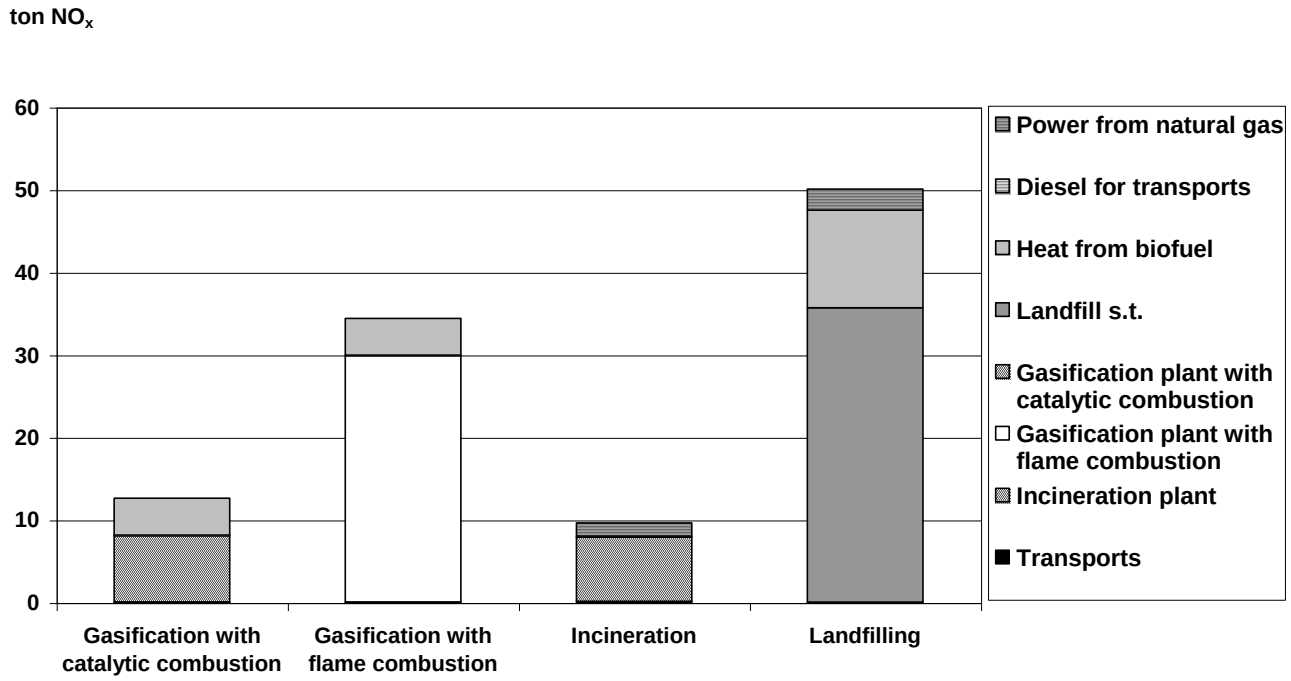

Figure 10.5 Emissions of NO_x

10.6 CONSUMPTION OF PRIMARY ENERGY CARRIERS

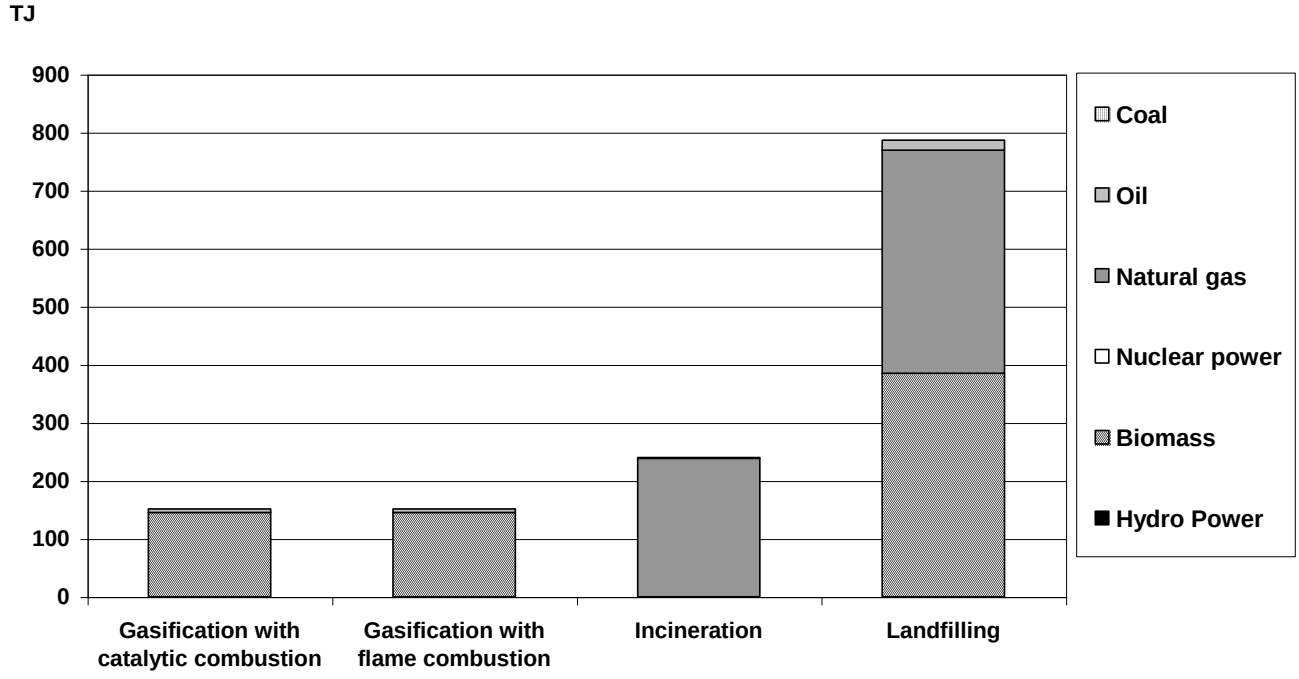

Figure 10.6 Consumption of primary energy carriers

10.7 FINANCIAL COSTS

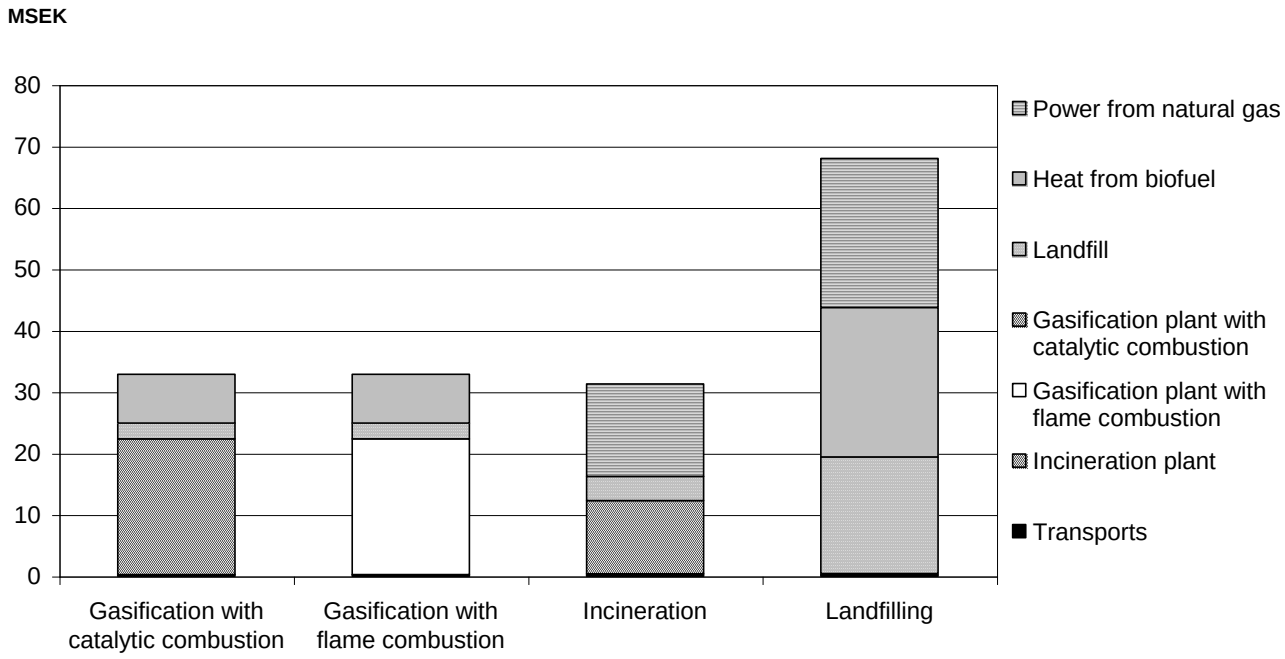

Figure 10.7 Financial costs for total system

10.7.1 Financial costs for core system

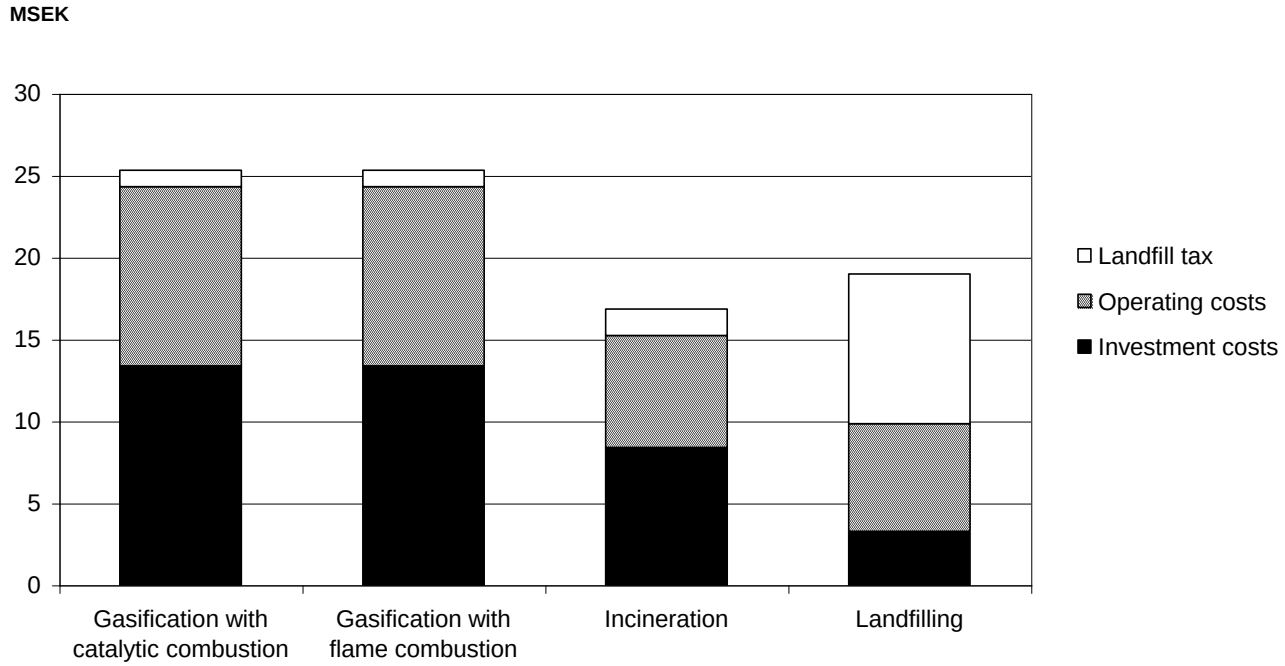

Figure 10.8 Financial costs in the core system

10.8 WELFARE COSTS

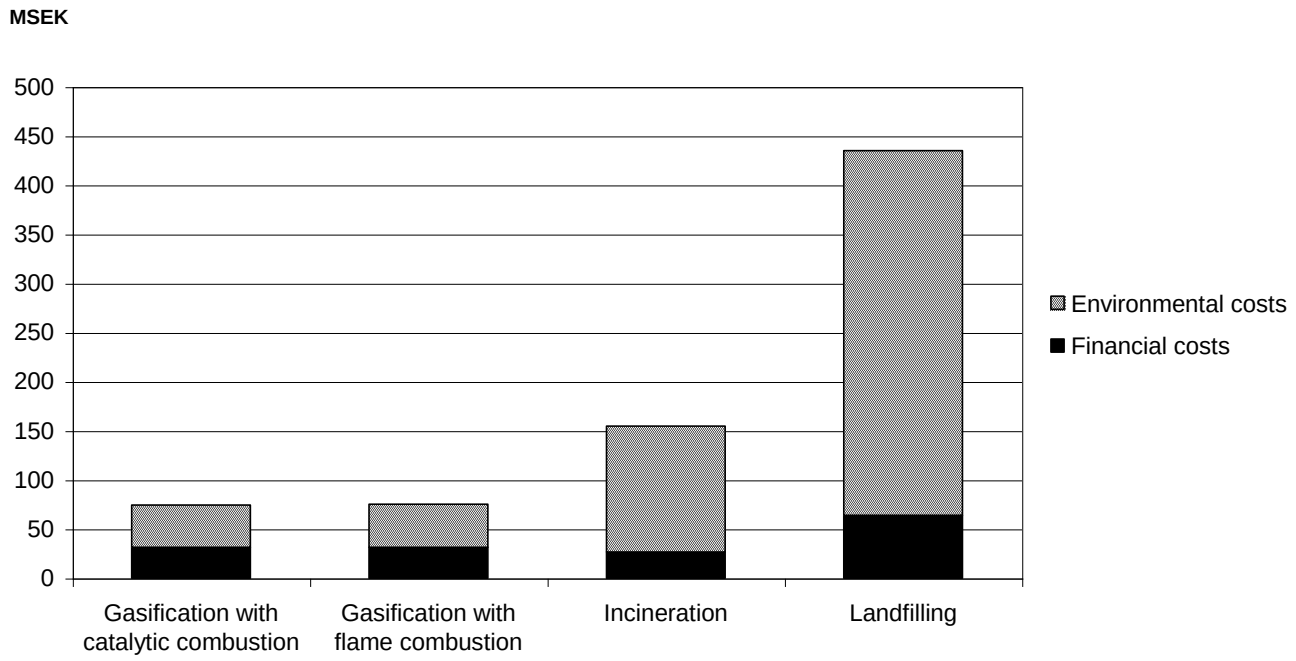

Figure 10.9 Welfare costs

11 APPENDIX 2 MODEL DESCRIPTION

This appendix contains information about the input data used in ORWARE model. The aim of this documentation is in order to have all the information used in the model documented or referred here. The appendix is limited only to contain the input data or the data used by the model for simulation. No results are presented here. This model description contains general and common information. The input data to the ORWARE model is a lot of figures and quite detailed and most of it has been published in a number of previous publications. Submodels described in previous publications are described shortly with a reference to relevant published materials. Some submodels are only described in terms of the change made in them as an update to their published material. For new submodels and previously unpublished material, a more detailed model description with all input data used is given.

Wherever necessary, specific input data and assumptions made in this study and some modifications done on previously existing submodels are included in this appendix.

11.1 WASTE DESCRIPTION

ORWARE is composed of submodels that can handle different types of waste and wastewater such as waste from households and business firms, black water and grey water. Different types of special wastes such as bulk waste, hazardous waste and radioactive waste are not part of the waste stream in ORWARE. The waste generated by the waste management system (ash, slag, sludge) is taken care of by the model.

11.1.1 Fractions/composition

The current version of ORWARE takes into account twelve different fractions of household waste that can be treated separately or in combination. The reason for separating the waste into these twelve fractions is due to the availability of elemental analysis of composition for these twelve types of waste fractions. This has been a problem regarding site specific studies since it is seldom that municipalities have such a detailed data. Analysis of different fractions of household waste is available in the following references;

1. Berg et al, 1998
2. Fellers et al, 1996
3. Nordesjö et al, 1988
4. SKAFAB, 1993
5. SIS, 1994
6. Sjöström, 1993
7. Sundqvist et al, 1991
8. Sundqvist et al, 1997
9. Sonesson et al, 1996

Table 11.1 shows the chemical composition of different fractions of household waste. The composition is calculated as an average value of the aforementioned references as indicated by numbers in the brackets on the heading of each fraction in the table.

Table 11.1 Elementary composition of different fractions of household waste

(kg/kg TS)	HHV (MJ/kg)	Organic household waste (9)	Non combustible remaining fraction (1)	Combustible remaining fraction (2,6 and 7)	Cardboard (1,4,5 and 8)	Diapers (1)	Rubber (1,5 and 7)	Dry paper (1,4,7 and 8)	Laminate (4)	Glass (5 and 7)	Metal (1)	Mixed plastic (1,4,5 och 8)
C tot-fossil	-	0	0	0	0,085	0,38	0,58	0	0,24	0	0	0,73
C-tot biological of which	-	0,434	0	0,48	0,40	0,21	0	0,47	0,24	0	0	0
C-lignin	40,89	0,029	0	0,16	0,059	0	0	0,033	0,036	0	0	0
C-cellulose	37,51	0,107	0	0,34	0,34	0,21	0	0,31	0,2	0	0	0
C-sugar	39,57	0,097	0	0	0	0	0	0	0	0	0	0
C-fat	51,25	0,135	0	0	0	0	0	0	0	0	0	0
C-protein	45,07	0,066	0	0	0	0	0	0	0	0	0	0
VS	-	0,8	0,09	0,85	0,94	0,89	0,87	0,87	0,85	0	0	0,97
VOC	50,10	$2{,}00*10^{-06}$	0	0	0	0	0	0	0	0	0	0
CHX	35,00	$1{,}00*10^{-08}$	0	0	0	0	0	0	0	0	0	0
PAH	-	$5{,}00*10^{-07}$	0	0	0	0	0	0	0	0	0	0
Phenols	-	$2{,}75*10^{-05}$	0	0	0	0	0	0	0	0	0	0
PCB	-	$4{,}35*10^{-08}$	0	0	0	0	0	0	0	0	0	0
Dioxin	-	$9{,}00*10^{-14}$	0	0	0	0	0	0	0	0	0	0
O	-	0,287	0	0,38	0	0	0,11	0,47	0	0	0	0,048
H	-	0,058	0	0,06	0,069	0,079	0,089	0,064	0,069	0	0	0,12
N tot	-	0,020	0	0,002	$2{,}60*10^{-03}$	$1{,}30*10^{-02}$	$8{,}70*10^{-02}$	$2{,}80*10^{-03}$	$3{,}00*10^{-03}$	0	0	$3{,}00*10^{-03}$
NH_3/NH_4-N	-	0	0	0	0	$8{,}40*10^{-03}$	0	0	0	0	0	0
S tot	-	$2{,}40*10^{-03}$	0	0,001	$1{,}20*10^{-03}$	0	0,011	$1{,}20*10^{-03}$	$7{,}00*10^{-04}$	0	0	$1{,}50*10^{-03}$
P tot	-	$3{,}80*10^{-03}$	0	0	$4{,}70*10^{-04}$	$9{,}90*10^{-04}$	0	$2{,}00*10^{-04}$	$4{,}20*10^{-04}$	0	0	$8{,}20*10^{-04}$
Cl	-	$3{,}90*10^{-03}$	0	0,002	$1{,}70*10^{-03}$	0	$2{,}20*10^{-02}$	$8{,}50*10^{-04}$	$3{,}60*10^{-03}$	0	0	$3{,}80*10^{-02}$
K	-	$9{,}30*10^{-03}$	0	0	$1{,}20*10^{-03}$	$3{,}30*10^{-03}$	0	$1{,}40*10^{-03}$	$1{,}20*10^{-03}$	0	0	$1{,}50*10^{-03}$
Ca	-	0,028	0	0	$1{,}40*10^{-02}$	$9{,}10*10^{-04}$	0	$1{,}90*10^{-02}$	$9{,}80*10^{-03}$	0	0	$4{,}90*10^{-03}$
Pb	-	$1{,}00*10^{-05}$	$5{,}00*10^{-06}$	$19{,}0*10^{-06}$	$8{,}30*10^{-06}$	$5{,}00*10^{-06}$	$2{,}10*10^{-06}$	$1{,}30*10^{-05}$	$1{,}80*10^{-05}$	0	$1{,}80*10^{-04}$	$2{,}10*10^{-04}$
Cd	-	$1{,}30*10^{-07}$	$1{,}00*10^{-07}$	$5{,}00*10^{-07}$	$1{,}40*10^{-07}$	$3{,}00*10^{-07}$	$2{,}10*10^{-07}$	$1{,}80*10^{-07}$	$5{,}10*10^{-07}$	0	0	$3{,}70*10^{-07}$
Hg	-	$2{,}80*10^{-08}$	$5{,}00*10^{-08}$	$2{,}80*10^{-08}$	$4{,}00*10^{-08}$	$5{,}00*10^{-08}$	$3{,}40*10^{-08}$	$2{,}10*10^{-08}$	$3{,}00*10^{-08}$	0	0	$6{,}00*10^{-08}$
Cu	-	$3{,}40*10^{-05}$	$1{,}50*10^{-05}$	$53{,}0*10^{-06}$	$1{,}90*10^{-05}$	$5{,}00*10^{-06}$	$8{,}80*10^{-06}$	$4{,}10*10^{-05}$	$1{,}50*10^{-04}$	0	$4{,}70*10^{-03}$	$1{,}50*10^{-04}$
Cr	-	$1{,}00*10^{-05}$	$5{,}80*10^{-05}$	$21{,}0*10^{-06}$	$7{,}30*10^{-06}$	$5{,}00*10^{-06}$	$2{,}90*10^{-05}$	$7{,}30*10^{-06}$	$8{,}60*10^{-06}$	$1{,}80*10^{-05}$	$1{,}10*10^{-03}$	$1{,}60*10^{-05}$
Ni	-	$7{,}00*10^{-06}$	$1{,}90*10^{-05}$	$31{,}0*10^{-06}$	$5{,}30*10^{-06}$	$2{,}00*10^{-06}$	$3{,}10*10^{-06}$	$5{,}40*10^{-06}$	$4{,}80*10^{-06}$	0	$5{,}30*10^{-04}$	$7{,}60*10^{-06}$
Zn	-	$8{,}00*10^{-05}$	$1{,}30*10^{-05}$	$3{,}50*10^{-04}$	$3{,}40*10^{-05}$	$4{,}70*10^{-05}$	$1{,}10*10^{-04}$	$5{,}60*10^{-05}$	$1{,}20*10^{-04}$	0	$2{,}00*10^{-04}$	$3{,}30*10^{-04}$
Mixed Plastic	38,94	0	0	0	0	0	0	0	0	0	0	1
Polyethene plastic	46,00	0	0	0	0,1	0	0	0	0	0	0	0
TS (kg/kg waste)	-	0,3	0,76	0,92	0,79	0,28	0,92	0,88	0,84	1,0	1,0	0,95

The fuel input used in this study is pellets produced from industrial wastes. However in both the landfilling and incineration scenario the industrial waste is taken to treatment as it is. Due to the lack of data concerning the industrial waste used to produce the pellets, there was a need to make assumptions regarding the moisture content of the original waste. That is assumed to be 70 %. The chemical composition of the pellets and the composition of the waste corresponding to this TS value look like as depicted in Table 11.2.

Table 11.2 Chemical composition of industrial waste pellets and corresponding waste

Substance	kg/kg pellets[1]	kg/kg waste
Ctot-b of which	0.4146	0.31
Cch-stable, lignin	0.0277	0.02
Cch- biodegradable	0.0927	0.07
C-fat,	0.129	0.09
C-protein,	0.063	0.05
Cch-medium	0.102	0.075
Ctot-f	0.02073	0.0153
VS	0.795	0.59
TS	0.951	0.70
O-tot	0.3329	0.25
H-tot,	0.0523	0.04
H_2O	0.049	0.30
N-tot	$1.9*10^{-3}$	$1.40*10^{-3}$
S-tot	$1.2*10^{-3}$	$8.83*10^{-4}$
P-tot	$1.72*10^{-4}$	$1.25*10^{-4}$
Cl-tot	$2.28*10^{-3}$	$1.68*10^{-3}$
K	$7.63*10^{-4}$	$5.62*10^{-4}$
Ca	$3.2*10^{-2}$	$2.33*10^{-2}$
Pb	$2.53*10^{-6}$	$1.86*10^{-6}$
Cd	$3.88*10^{-8}$	$2.86*10^{-8}$
Hg	$2.04*10^{-8}$	$1.50*10^{-8}$
Cu	$7.3*10^{-3}$	$5.37*10^{-3}$
Cr	$1.91*10^{-5}$	$1.41*10^{-5}$
Ni	$2.68*10^{-6}$	$1.97*10^{-6}$
Zn	$8.18*10^{-5}$	$6.02*10^{-5}$
Magn. metal (Fe)	$7.7*10^{-4}$	$5.67*10^{-4}$
Ash	0.156	0.11

Table 11.3 depicts heat values for petrol and diesel (EcoBalance) and methane (Wester 1993) used in different parts of the model.

Table 11.3 Energy values used in the model

Energy carrier	Low heating value	Unit
Petrol	40.8	MJ/kg
Diesel	42.8	MJ/kg
Methane	55.5	MJ/kg

[1] source : laboratory analysis from SGAB Analytica.

11.1.2 Waste and pellets amount

The amount of waste and their percentile composition of the fractions shown earlier vary from region to region. However the amount of waste pellets that is used in the study is calculated based on the amount required to produce 4 MW electricity and 8 MW heat according to calculations made by Andersson et al. (1999). This amount is 24 000 ton of industrial waste pellets per year. With a TS value of 70 %, this amount of pellets corresponds to 32 600 tonnes of industrial waste. While producing the pellets from the industrial waste, heat for drying amounting to heat of vaporisation with an efficiency of 90 % and electricity of 50 MJ/ton2 of waste is consumed.

11.2 SUBMODELS IN THE WASTE MANAGEMENT SYSTEM

11.2.1 Collection

Collection sub model is documented in Sonesson (1996), and article IV in Sonesson (1998). This collection model for garbage lorry is used for calculating the energy use, emissions and costs for collection and transport of waste. Information about the distance to collection areas and average speed to the collection area, amount of waste collected, the average load of lorry, number of stops, time spent at each collection point, distance between collection points, average speed during collection is required. These data are used to calculate the energy consumption, the total time required and the cost. The total emissions are in turn calculated from the energy consumption. It is considered in this study that collection work is outside the system studied since it is the same for all scenarios studied.

11.2.2 Transports

Transport model is described in Sonesson (1996).

Models for trucks with and without trailer are used for calculating energy consumption, emissions and cost for transport of materials from one place to another. The difference between these trucks and the collection trucks is that loading and unloading is assumed to be such a insignificant part of the transport that it is left out of te model. Otherwise submodels are identical in their structure differing only in the input data concerning fuel consumption, loading capacity etc. The model structure is shown in Figure 11.1.

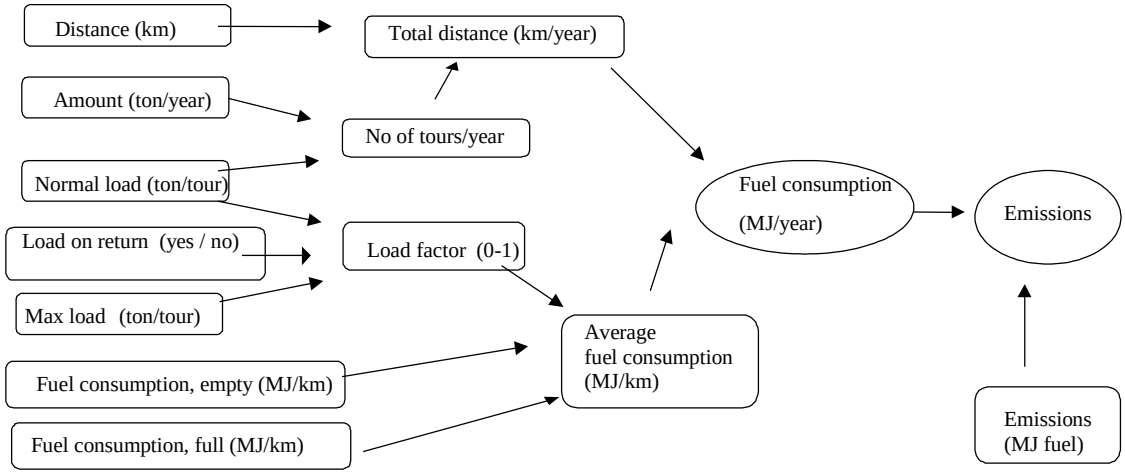

Figure 11.1 Model structure for transport models

[2] Personal communication with Folke Giesen, SITA Sverige AB.

The number of loads required per year in the transport model is calculated from the amount of material to be transported and the normal load capacity for the specific type of material. The number of loads together with the distance between source and destination gives total drive distance per year. This total drive distance in turn is used for two purposes:

1. To calculate total fuel consumption using average fuel consumption per km

2. By using average speed, the total drive time per year is obtained which in turn gives the number of trucks required paving the ground for fixed cost calculation. The total drive time is also used for calculation of variable costs (e.g. salary etc.) that are functions of time consumed for transport.

Normal load and max load together with information about whether the truck is loaded on return or not gives basis for the load factor i.e. how much of the maximum load the actual average load is (e.g. if the truck is fully loaded in one way and empty on the way back the load factor is 0.5). This load factor and data about fuel consumption both during max load and empty load gives the average fuel consumption. The total fuel consumption is used together with emissions per MJ of fuel consumed, to calculate emissions per year. Furthermore the total fuel consumption is used to calculate costs for fuel. Finally the total cost for transport is obtained as the sum of variable cost, fixed cost and fuel consumption.

The structure of the model provides flexibility in different ways. Materials with lower density result in a higher number of loads with low average fuel consumption which is in line with the reality. It is simple to change many parameters so that changes in prices etc can be made. The biggest drawback lies in the assumption of the average speed which regulates the drive time and in turn much of the cost calculations. This average speed thus should reflect the speed during the transport of the material during one year including loading, unloading and the working days spent for maintenance etc. This is of course difficult to estimate. Currently the average speed is calculated by dividing normal drive distances per year for long distances by the number of working hours per year. Table 11.4 shows input data in transport models, Table 11.5 shows emission data per MJ.

Table 11.4 Input data for transport models

Input data	Value
Max load, truck	12 ton
Max load, truck and trailer	35 ton
Average speed	30 km/h *
Fuel consumption truck, empty	2 litre / 10 km
Fuel consumption truck, full load	3.5 litre / 10 km
Fuel consumption trailer, empty	3 litre / 10 km
Tyre wear	0.027 g tyre / MJ consumed fuel
Fuel consumption truck and trailer, full load	5 litre / 10 km

* corresponding to a use of a truck for 1760 h/year and annual drive distance of about 5 00 km.

Table 11.5 Emissions to air from trucks

Emission	g/MJ
CO_2 - fossil	74
CH_4	0.001
VOC	0.066
PAH	0.0000025
CO	0.00029
NO_x	0.53
N_2O	0.0026
SO_x	0.093
particles	0.013

For this specific study, data for transport of pellets is as shown in Table 11.6 (truck and trailer) and Table 11.7 (truck without trailer).

Table 11.6 Transports, truck and trailer with max load of 35 ton

Load	From	To	Distance [km]	Normal load [ton]
Slag and stabilised ash	Incineration	Landfill	35	35
Moist fly ash	Incineration	Landfill	35	35
Gasification residues	Gasification	Landfill	30	35

Table 11.7 Transports, truck without trailer with max load 20 ton

Load	From	To	Distance[km]	Normal load[ton]
Waste	Collection centre	Landfill	5	20
Waste	Collection centre	Incineration	30	20
Pellets	Pellet production	Gasification	2	20

The collection centre and the pellet production site are assumed to be located not far from each other.

11.2.3 Incineration

The incineration model is described in Björklund (1998), appendix E.

The data used for calculations is from 1996. Currently there are two types of the model, one describing the incinerator in Uppsala operated by Vattenfall (former Uppsala Energy) and the second model for Birka Energy's incinerator at Högdalen in Stockholm. The model for Stockholm has been modified and further developed compared to the one described in Björklund (1998), appendix F. The changes made are shown in a project report to the Swedish Energy Administration (Sundqvist et al., 2002). In both cases the models are site specific and use emission and mass flow data measured at these facilities. The model is built up of three parts: pre-treatment, incineration chamber and flue gas cleaning. Figure 11.2 gives a schematic diagram of the structure valid for both models.

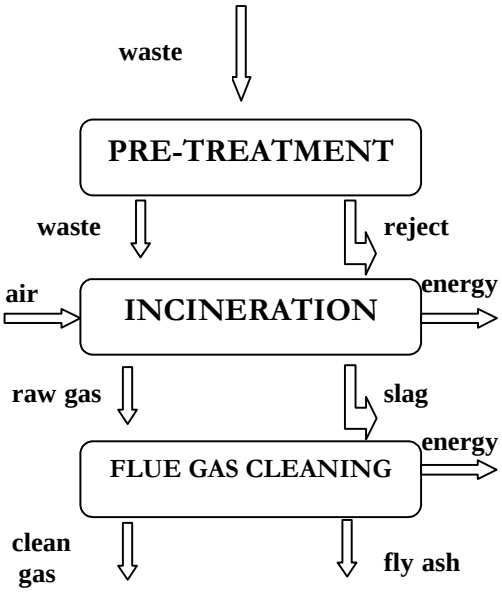

Figure 11.2 Structure of the incineration model

11.2.3.1 Pre-treatment

In the pre-treatment stage some parts of the incoming waste are separated for compression, wrapping and enclosing in plastic. This possibility of wrapping can be utilised at times when the amount of incoming waste is higher than the capacity of the incinerator. This situation sometimes occur in the summertime when parts of the incineration facility are closed for maintenance. To avoid landfilling of combustible waste from the same municipality or waste from another municipality for landfilling somewhere else, the wrapping alternative is preferred.

In terms of modelling this would mean 2 kg plastic/ton of waste and electricity consumption of 14.5 MJ/ton waste. This data for wrapping is obtained from Åberg (1998).

11.2.3.2 Incineration

In the incineration chamber mixed waste is incinerated where an impure flue gas or raw gas is built up. Non-combustible part is separated in the form of slag. The raw gas is then taken to flue-gas cleaning facility where gas cleaning is performed with calculation of associated energy recovery, see figure A2. As part of the raw gas cleaning, condensation equipment and a water treatment facility to treat the condensed water are included. The gas cleaning part gives one stream of fly ash and another stream of clean gas.

11.2.3.3 Flue gas cleaning

Separation of pollutants and partitioning of substances is carried out in the model to the largest extent using a material balance. This is related to either the amount of a specific incoming substance or the total amount of incoming waste. It is found to be logical to relate certain emissions to the prevailing permissible values e.g. for NO_X which is linearly dependent on the energy content of the waste. A material balance is not applied for such substances in the model. During incineration in both submodels, different components are partitioned as follows:

Heavy metals. In the model, how much of the metals in the incoming waste that end up in the slag and raw gas is calculated first. Then calculation is made for how much of the metals in the raw gas that goes to fly ash, sludge and wastewater, and emissions to air. The fly ash and sludge are mixed together to give a stabilised cement-like material. Emissions to water and air are proportional to the amount of metals in the waste. Emissions to air for all heavy metals except mercury are less than 0.5 % of incoming amount. The

ash and sludge resulting from the flue gas cleaning part and the slag from the incineration chamber are transported to a waste landfilling.

Nitrogen oxide and laughing gas. Nitrogen oxide emissions and laughing gas emissions are calculated based on the energy content. This depends on the fact that permissible amount of NO_x emissions is given in units of kg NO_X/MJ.

Sulphur oxides. Calculations are done in the same way as for nitrogen oxides.

Dioxins. Dioxin emission is calculated from the amount of waste incinerated.

Heat production. The model calculates the heat from the energy content of the waste based on its composition. The energy recovery is calculated using the effective heating value and the moisture content of the waste. In the flue gas condenser about 70 % of the theoretically available heat of the steam is recovered.

Chemical additives. The number and amount of additives varies based on the facility.

General input data to incineration model is shown in Table 11.8.

Table 11.8 Input data in the incineration model

Parameter		Unit
Plastic used in wrapping	0.002	kg plastic /kg waste
Electricity consumed in wrapping	0.0145	MJ el /kg waste
Condensation efficiency	0.70	MJ heat/MJ in flue gas

The basis for the model used in this project is the waste incineration facility at Högdalen in Stockholm with the latest performance data from the environmental report of the facility for the year 2000. Rest products from the facility like ash and slag are landfilled. In Table 11.9 the parameters of incineration are described. Note that the NO_X emission value is based on the threshold value not on the actual measured value which is lower than the former.

Table 11.9 Performance parameters for incineration process.

Parameter	Value	Unit
Total efficiency	88	% of lower heat value
NO_X - emission till air	45	mg NO_2/MJ waste
	36	ppm NO_2
N_2O - emission till air	10	mg N_2O/MJ waste
Dioxin formation	0.10	pg dioxin/kg waste
SO_2-separation in flue gas cleaning	95	%
HCl- separation in flue gas cleaning	99.8	%
Alpha value for heat power operation	0.28	MJ el/MJ heat

11.2.4 Landfilling

Landfilling model is fully described in Björklund (1998), appendix D and in Fliedner (1999).

Five different types of landfilling are modelled; biocell (Fliedner, 1999), landfilling for mixed waste, sludge landfilling, ash landfilling and slag landfilling (Björklund, 1998). The models are supposed to reflect Swedish average landfilling and site specific modification of the models is limited. Normally it is only methane extraction and leakage treatment that varies.

Waste being landfilled today will continue to produce emissions for a long time in the future. One dilemma is, thus, how to compare such emissions from landfilling with more immediate emissions from other processes in the system. To include only the immediate emissions from landfilling would not be a logical representation of the total load. On the other hand to try to estimate the total emission brings about a considerable magnitude of uncertainty and even so the time perspective becomes incomparable with the other processes. As a compromise, future impacts of landfilling have been divided into two time periods that have some differences for the different types of landfilling (see Figure 11.3):

Surveyable time (ST): During this time most of the reactive processes in the landfill get subsided and the landfill apparently reaches a stationary condition. For mixed waste and sludge as well as biocell, the surveyable time is defined as the end of the methane generation phase. For slag and ash landfills the leakage of soluble salts defines the surveyable time. The surveyable time is consequently a functional measure of time and varies from case to case but generally it is in the order of 100 years.

Remaining, infinite time (RT): This time period covers the time until all the landfilled material is spread out in the environment through the formation of gas, leakage, erosion and possible inland icing. This infinite time embodies emissions in the worst scenario.

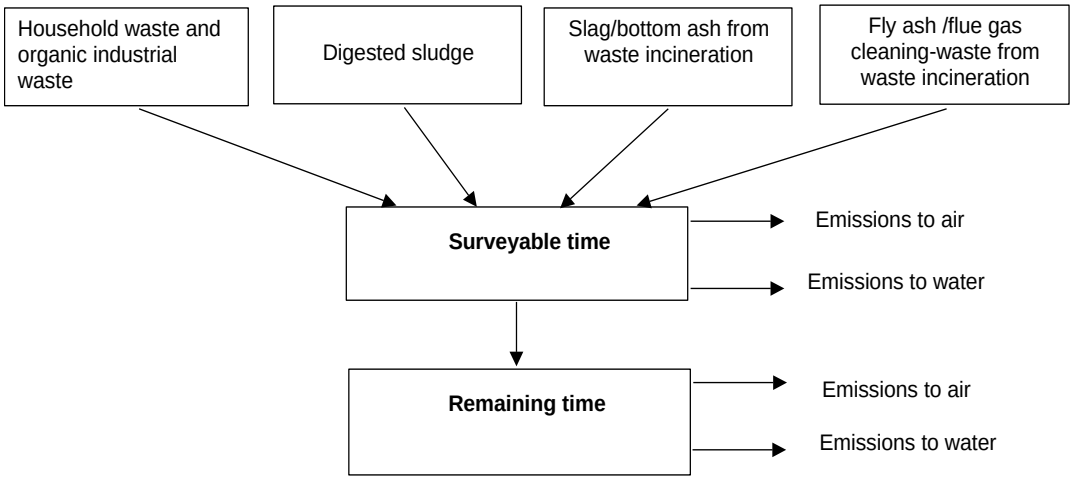

Figure 11.3 Material flow structure in the landfilling model

Calculations are based on the amount of waste landfilled during one year. The emission during the surveyable time is an average yearly emission under corresponding time from a landfill where the same amount of waste is landfilled year after year. When emissions under this surveyable time are calculated, the emissions that will occur during the remaining time are also calculated. During assessment and discussions attention is paid only to those emissions under the surveyable time. In the submodels for landfilling of mixed waste and sludge, the following processes occur:

- Degradation of organic material produce emissions composed of mainly methane. Sugar, starch and fat are considered to be 100 % degradable, cellulose 70 % while lignin and plastic as non-degradable. The composition of the gas varies depending on composition of the organic material. In most of the cases, the gas contains 50 – 60 % CH_4 and the rest mainly CO_2.

- Leakage of heavy metals is small during the surveyable time, in the range 0.1 to 0.001 % of the landfilled amount.

- Nutrient leaks in the form of phosphorus (2 % of amount landfilled, 15 % for sludge) and nitrogen (90 % of landfilled amount).

- For organic pollutants, there is lack of knowledge concerning their long term fate in landfills. During the surveyable time, it is possible that such substances are formed, degraded, converted

to gas, vaporised, leak out or adsorbed to the landfilled material. A very simplified estimate for every substance is studied.

- The gas can be collected during the surveyable time with an efficiency of 50 % of the gas formed. The collected gas can be flared out or combusted in a gas motor. The remaining gas makes its way to the outer layer of the landfill where 15 % of the methane is oxidised to carbon dioxide.

The biocell model that handles only easy degradable organic waste is based on the landfill for mixed household waste. However, it gives considerably faster degradation (i.e. the surveyable time refers to a shorter time) and more effective gas collection than in conventional landfilling (65 % of formed gas). Furthermore a leakage water of higher quality is formed. In this connection, a biocell is considered to be something between a conventional landfill and a digestion chamber.

The main feature of landfilling of ash and slag is leakage of heavy metals. Metals in the ash leak out in the range of 1 to 10 % of landfilled amount during surveyable time. Metals in the slag are less leakable corresponding to 0.1 to 5 % of landfilled amount under the surveyable time. No gas is extracted from such landfills.

The leakage treatment model can be connected to all of the landfill submodels. The model reflects a biological treatment with a chemical precipitation. About 80 % of the phosphorus leaking out under the surveyable time is collected and recycled back to the landfill (it then leaks out during the remaining time). Furthermore 90 % of the nitrogen leakage is partitioned as nitrogen gas with the rest going out with the leakage water. No metal partitioning is modelled. Working machines consume 40 MJ of diesel oil per ton of landfilled material in all submodels. Table 11.10 depicts input data for landfilling sub model.

Table 11.10 Parameters in landfilling models under the surveyable time

Parameter	value	Unit
degradation of sugar, starch, fat	100	% of landfilled amount
degradation of cellulose	70	% of landfilled amount
degradation of lignin och plastic	0	% of landfilled amount
Leakage of phosphorus	2	% of landfilled amount
Leakage of nitrogen	90	% of landfilled amount
Leakage of heavy metals, MSW and sludge	0.1 – 0.001	% of landfilled amount
Leakage of heavy metals, incineration ash	1 - 10	% of landfilled amount
Leakage of heavy metals, incineration slag	0.1 - 5	% of landfilled amount
treatment efficiency, N in leakage water	90	% of leak water content
treatment efficiency, P in leakage water	0.8	% of leak water content
Gas collection, mixed waste and sludge	50	% of generated gas
Gas collection, biocell	65	% of generated gas
Soil oxidation, methane	15	% of methane leakage
Diesel consumption, all landfills	40	MJ/ton landfilled material

The gas (methane) recovered from landfilling can be used as a fuel in a gas motor that can produce electricity and heat. The energy from gas motor is calculated by using the energy content of the methane gas. If the gas is flared out, the emissions are calculated according to Table 11.11, with a zero energy recovery. When it is recovered, 30 % is electricity and 60 % heat but this also varies from case to case.

In this study, when the industrial waste is landfilled 50 % of the landfill gas produced is assumed to be collected (this is the same as for landfilling of organic waste). Around 90 % of this collected gas is used for heat production in a gas motor. Treatment of leakage water (nitrogen and phosphorus) is supposed to be part of both types of landfilling (landfilling of industrial waste and landfilling of ashes and slag). Whenever results for landfilling are shown, they refer only to the emissions during the surveyable time.

Table 11.11 Emissions from incineration of methane gas from landfilling in a stationary gas motor (mg/MJ gas)

Substance	Emission [mg/ MJ gas]
CH_4	100
VOC	160
CO	250
NO_x	200
Particles	0

11.2.5 Gasification

The gasification process modelled here is a TPS atmospheric gasification process using air as a gasifying agent. During the gasification process both partitioning and formation of components occur. The pellets are gasified into fuel gas resulting in a remaining ash component. Table 11.12 shows the partitioning coefficients used in the study. It is important to point out that most of the heavy metals end up in the bottom ash except for Copper that continues with the fuel gas until it is trapped by downstream filter unit.

Table 11.12 Partitioning coefficients of gasification of industrial waste pellets

Component	Ash fraction [kg/kg in waste]	Fuel gas fraction [kg/kg in waste]
Ctot-b	0	1
O-tot	0	1
H-tot	0	1
H2O	0	1
N-tot	0	1
S-tot	0.143	0.2910
P-tot	0.743	0.2568
Cl-tot	0	1
K	1	0
Ca	0.824	0.1762
Pb	0.794	0.2060
Cd	0.612	0.3881
Hg	0.761	0.2389
Cu	0.026	0.9738
Cr	0.857	0.1429
Ni	1	0
Zn	0.709	0.2910
Ctot-f	0	1
Fe	1	0
ash	1	0

In addition to those splitting up into two streams during the process, there are components formed during the gasification, see Table 11.13.

Table 11.13 Formation coefficients for gasification of industrial waste pellets

Component	Value	Unit
CO_2 biological	1.142	kg/kg Ctot-b
CO_2 fossil	1.142	kg/kg Ctot-f
CO	0.86020	kg/kg Ctot-f
H_2	0.0499	kg/kg Ctot-f
NH_3	0.18	kg/kg N
H_2S	0.233	kg/kg S-tot
H_2O	9	kg/kg H-tot

11.2.6 Flame combustion and catalytic combustion

The emission data for the flame combustion process modelled here is based on different sources such as Värnamo plant (Sydkraft, 2001) with some modifications and estimations. Table 11.14 depicts partitioning coefficients that decide how much of each component that is accounted for in the modelling. The remaining part is not accounted for, or in other words; an assumption that there is no difference in the partitioning of components between the catalytic- and the flame combustion. Parts of the entering components that are not leaving with the flue gas from the catalytic combustion are assumed to be adsorbed onto the catalysts.

Table 11.14 Partitioning coefficients of flame and catalytic combustion of gasified waste

Component	kg in flue gas per kg in entering fuel gas
Ctot-b	0.0002
S-tot	0.181
P-tot	0.960
Cl-tot	0.009
K	0.924
Ca	0.996
Pb	0.248
Cd	0.006
Hg	0.224
Cu	0.607
Cr	0.987
Ni	0.481
Zn	0.249
Ctot-f	0.0002
Fe	0.921
Ash	0.90

The data shown on Table 11.15 displays the amount of pollutants formed during the course of flame combustion and catalytic combustion of gasified waste. When it comes to the amount of pollutants such as CO and NO_x formed, the difference between flame combustion and catalytic combustion is recognised. There is no difference in CO_2 and SO_X, while CO, NO_X and UHC show a difference.

Table 11.15 Formation coefficients of flame and catalytic combustion of gasified waste

Component	Flame combustion	Catalytic combustion	Unit
CO_2 biological	2.194	2.194	kg/ kg Ctot-b in fuel gas
CO_2 fossil	2.194	2.194	kg/ kg Ctot-f in fuel gas
UHC	$1.58*10^{-7}$	$1.58*10^{-8}$	kg/ MJ pellet
CO	$4*10^{-5}$	$4.526*10^{-6}$ (6 ppm)	kg/ MJ pellet
NO_X	$1.6*10^{-4}$	$4.3047*10^{-5}$	kg/ MJ pellet
NO_X	129	32 (fuel NO_x) + 2.5 (thermal NO_x)	ppm NO_2
SO_X	$3*10^{-5}$	$3*10^{-5}$	kg/ MJ pellet

11.2.7 The Economy submodels

The economic model is described in Carlsson (1997), but new models have since then been developed and most part of the original model in this publication has been changed. The following chapter is a brief description of the economic model. The cost is distributed over the calculated life time of the facility and other assets according to annuity method. This complies with the yearly-based calculations in ORWARE. The annuity function is given as:

$$a = \frac{k*(1+r)^t*r}{(1+r)^t-1}$$

where a = annual cost, SEK/year,

k = capital investment,

t = depreciation time, year

r = interest, expressed in decimal form (5 % interest = 0.05)

General economic assumptions are as shown in Table 11.16.

Table 11.16 General assumptions the model

Parameter	Value
Rent	5 %
Salary	170 SEK/h
Working hours	1 760 h/person and year
Cost of rail way transport	20 SEK/ton*km

Furthermore different components of the waste management system consume oil and diesel (e.g. transport and treatment facilities). In the cases where the costs are not included in other ways, they are included according to Table 11.17.

Table 11.17 Price of oil and diesel in submodels

Fuel	Price
Fuel oil	26,23 öre/kWh (900 SEK/ton plus tax for sulphur, CO_2, energy)
Diesel oil, environmental class 2	4.20 SEK/litre
Petrol, 95 octane	8.90 SEK/litre

11.2.7.1 Collection and transport

The economic model for transport and collection is dependent on different input data from the technical part of the ORWARE model such as man hours, truck hours and fuel consumption. The cost for trucks is thus dependent on the transport distance, average speed while for garbage lorry on length of collection round, distance to collection area, and time required for the collection work (see Figure 11.4).

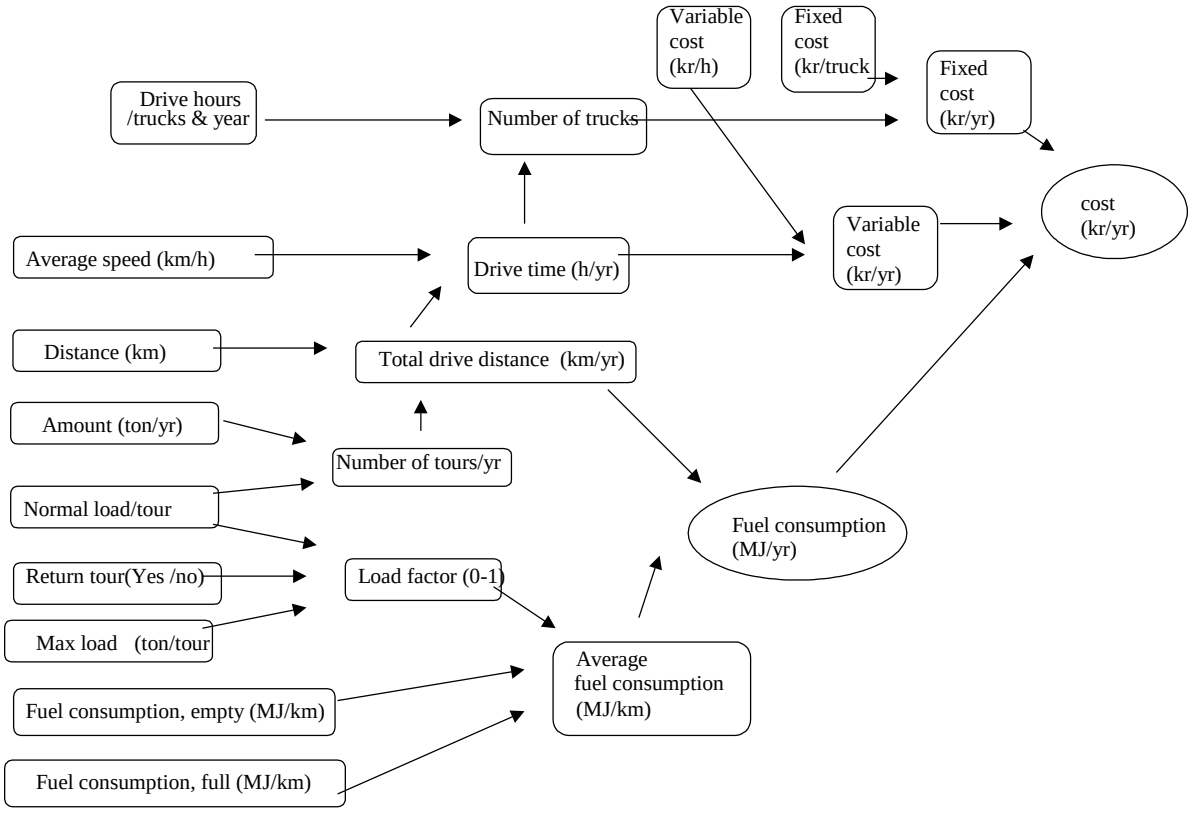

Figure 11.4 Flow scheme for cost calculation for transport

The economic data input for the different transport and collection models is taken from RVF (1992), and truck centre in Uppsala (LBC, 1998) according to Table 11.18 and 11.19.

Table 11.18 Input data for calculation of transport cost

Parameter	Value	Reference
Cost for truck	1 300 000 SEK	LBC (1997)
Life time	7 years	
Cost for trailer	2 000 000 SEK	LBC (1997)
Life time	7 years	
Fixed cost per car and year	54 000 SEK	RVF (1992)
Drive time per car and year	1 700 h	RVF (1992)
Maintenance per km drive distance	2.60 SEK	RVF (1992)

Table 11.19 Input data for calculation of collection cost

Parameter	Year	Reference
Cost for lorry	1 100 000 SEK	RVF (1992)
Life time	7 years	
Cost for front loader	1 700 000 SEK	LBC (1997)
Life time	7 years	
Fixed cost per car and year	54 000 SEK	RVF (1992)
Drive time per car and year	1 700 h	RVF (1992)
Maintenance per km drive distance	2.6 SEK	RVF (1992)

11.2.7.2 Incineration

The economic model for incineration is based on Dalroth (1998). Those function used for cost calculations are shown Table 11.20.

Table 11.20 Cost assumptions for the incineration facility

Parameter	Value
Investment, Heat power	Capacity ^{0,68}*145 000
Investment, Heat	Capacity^{,68}*145 000*0.55
Depreciation	20 years
Effect, MW	Capacity *0.38*10^{-3}
Personal	$10+(14.3*\text{effect}+200)^{0,5}$ (rounded upwards)
Maintenance and operating costs	2.5% of investment
Chemicals and lime	20 SEK/ton waste

Capacity = capacity of the facility, ton/year

As mentioned previously when the incineration plant is closed for an overhaul, the waste is wrapped instead of sending it to a landfill. The cost of running such a wrapping facility is based on Åberg (1998), and shown in Table 11.21.

Table 11.21 Data for wrapping facility

Parameter	Value
Wrapping machine	3 800 000 SEK, depreciation time 10 years
Capacity	12 000 ton/year
Maintenance	4 % of investment per year
Running cost	human power: 2 men
	Cost plastic: 50 SEK/ton waste
	Electricity 14.4 MJ/ton waste

This gives a cost of ca 145 SEK/ton on a 5 % interest.

11.2.7.3 Landfilling

The model is based on the information from biocell, Persson (1997). The data is shown in Table 11.22.

Table 11.22 Cost for biocell

Capacity, ton/year	Investment, MSEK		Running cost, MSEK/year
	Land	Machinery	
3 600	1.5	3.9	1.4
4 100	2.1	4.3	1.5
17 400	3.8	10	3.3
28 800	3.8	11.1	5

For landfilling of slag and fly ash 80 % of the cost given above has been estimated by Fliedner (1999). The cost below is based on a gas motor used in Uppsala wastewater treatment facility, see Table 11.23.

Table 11.23 Input data for gas motor

Parameter	Value
Investment cost	5 MSEK
Life time	10 years
Operating cost	900 000 SEK/year

11.2.7.4 Gasification

The cost parameters used for gasification are included as parts of the cost for flame combustion and catalytic combustion as shown in Table 11.24 and Table 11.25.

Table 11.24 Economic parameters for flame combustion and catalytic combustion of gasified waste

Parameter	Flame combustion	Catalytic combustion
Investment cost, MSEK	153	153
Running Cost, MSEK	10	10
Depreciation time, years	20	20
Catalyst costs, MSEK	0	0.25

Table 11.25 Components of investment cost

Parameters	MSEK
Pellet preparation system	15
Gasification system	66
Gas turbine system	21
Ceramic filter	11
Fuel gas compressor	6
Heat Exchanger	10
Other(piping etc)	12
Total	**141**

11.3 SUBMODELS IN THE COMPENSATORY SYSTEM

The compensatory system is required in order to compare the service (functional units) obtained from the waste management system with services produced somewhere else. Supply of material and energy to the total system (waste management system and external system) is in the form of resources in nature i.e. uranium in intact uranium ore, oil in raw oil source, biomass as trees in forest, etc. Outflows from the system consist of specific amounts (based on the size of the functional units) of district heating (hot water), electricity, fertiliser (phosphorus and nitrogen fertiliser), vehicle fuel, PE-plastic and cardboard.

Environmental impact of the external production system covers the same part of the life cycle as the waste management system, i.e. only the operation phase. Environmental impact refers to emissions to air, soil and water as well as depletion of natural resource. The natural resource depletion includes only energy consumption in terms of primary energy carriers. In other words resources in the form of such materials as steel, copper, wood etc are not included.

For electricity from nuclear power plant, the thermal energy (the utilised electricity plus the heat lost) is used. For hydropower, the energy delivered from the power plant is used without considering the loss in the turbines and the distribution grid. Apart from nuclear power and hydropower, energy consumption and emissions are calculated all the way back to cradle. Downstream processes such as waste treatment of e.g. ash from electricity and heat production are included only for heavy metals. This is because of lack of life cycle inventory data. The economic effects include the whole life cycle i.e. the building phase is also included.

11.3.1 Power supply

Electricity is used in the waste management system for different treatment processes and in the external system for production of e.g. virgin cardboard. Besides electricity, wherever necessary is used to fill up the functional unit "electricity" (if the waste management system shows a net production of electricity). In the waste management system the electricity consumption is indicated in term of MJ el for every activity. This consumption can be connected to a alternative production method like coal condense power, Swedish average electricity mix, etc

Unlike the model for the waste management system, data concerning the electricity consumption in the external functions (electricity consumption for production of new plastic, new cardboard, synthetic fertiliser, vehicle fuel, heat and electricity) is different. No underlying modelling is done. Instead existing studies are used. For heat production for example, Vattenfalls' LCA study is used. If in the LCA of biofuel heat plant in Vattenfalls study, a Swedish average electricity mix is used, it is included in the emissions from the whole system. Electricity used in this study is considered to be produced from natural gas power plant

11.3.1.1 Natural gas

In our calculation, data for a power plant running on natural gas is used. This is justified since the purpose of the study is an assessment of future prospects where natural gas is of interest. Data is based on Vattenfall's LCA (1996) for natural gas power. The plant is supposed to be a planned natural gas fired CHP. The overall efficiency is 53 %. Table 11.26 and 11.27 show resource consumption and emission factors for electricity production from natural gas.

Table 11.26 Resource use for production of electricity from natural gas

Energy resource (MJ/MJ fuel)	Extraction	Use	Sum
Renewable			
Hydro power electricity	$4.87*10^{-5}$	$1.98*10^{-4}$	$2.47*10^{-4}$
Biomass	$8.79*10^{-7}$	$1.79*10^{-5}$	$1.88*10^{-5}$
Non renewable			
Nuclear power electricity	$7.29*10^{-6}$	$1.56*10^{-4}$	$1.63*10^{-4}$
Natural gas	$3.05*10^{-2}$	$5.27*10^{-5}$	$3.06*10^{-2}$
Oil	$2.32*10^{-2}$	$2.23*10^{-4}$	$2.34*10^{-2}$
Coal	$2.07*10^{-2}$	$5.75*10^{-5}$	$2.08*10^{-2}$

Table 11.27 Emission coefficients for production of electricity from natural gas

Emission to air (g/MJ fuel)	Extraction	Use	Sum
NO_x	$3.44*10^{-2}$	$2.09*10^{-2}$	$5.53*10^{-2}$
SO_2	$6.81*10^{-5}$	$1.14*10^{-3}$	$1.21*10^{-3}$
CO	$8.17*10^{-3}$	$2.02*10^{-2}$	$2.84*10^{-2}$
Particles	0	0	0
HC (NMVOC)	$4.64*10^{-3}$	$8.61*10^{-2}$	$9.07*10^{-2}$
CO_2	9.22	108	117
CH_4	0	0	0
N_20 (data is missing in ref.)	-	-	-

11.3.2 District Heating

District heating can be generated using different fuels. Following part is data for production of district heating using combustion of biofuel. This is because in the case that the waste is not used a fuel for producing district heating, the heat is assumed to be supplied by a district heating system running on biofuel.

11.3.2.1 Biofuel

Data for biofuel fired district heating system was obtained from Vattenfall (1996). The heat is assumed to be produced in a heat and power plant with flue gas condensation fired with a forest fuel and total efficiency of 90 % based on high heating value. The choice of heat power plant rather than heat plant does not actually give a significant difference in the result. Type and performance of the flue gas condenser is the important factor that affects the final result. Upstream flows such as extraction of forest resources, fuel refining and transport are included. Flows downstream of the operation phase such as emissions from landfilling of ashes are not included. These emissions are considered to be small enough to be left out of the study. Resource consumption and emission factors for district heating production from biofuel are shown in Table 11.28 and 11.29.

Table 11.28 Resource consumption for production of district heating (MJ useful energy) from forest fuel in heat power plant

Energy resource (MJ/MJ)	Extraction	Use	Sum
Renewable			
Hydro power	-	$7.46*10^{-6}$	$7.46*10^{-6}$
Biofuel	-	$6.72*10^{-7}$	$6.72*10^{-7}$
Non renewable			
Nuclear power	-	$6.21*10^{-6}$	$6.21*10^{-6}$
Natural gas	-	$4.81*10^{-5}$	$4.81*10^{-5}$
Oil	$3.53*10^{-2}$	$5.67*10^{-5}$	$3.54*10^{-2}$
Coal	-	$1.71*10^{-4}$	$1.71*10^{-4}$

Table 11.29 Emission factors for production of district heating (MJ useful energy) from forest fuel in heat power plant

Emission to air (g/MJ)	Extraction	Use	Sum
NO_x	$4.22*10^{-2}$	$5.03*10^{-2}$	$9.25*10^{-2}$
SO_2	$2.41*10^{-3}$	$9.17*10^{-3}$	$1.16*10^{-2}$
CO	$1.33*10^{-2}$	$4.58*10^{-2}$	$5.92*10^{-2}$
HC (VOC)	$3.86*10^{-3}$	$2.92*10^{-5}$	$3.89*10^{-3}$
CO_2 fossil	2.69	$2.64*10^{-2}$	2.71
CO_2 biological	0	92	92
N_2O	0	$5.88*10^{-3}$	$5.88*10^{-3}$
CH_4	0	$5.88*10^{-3}$	$5.88*10^{-3}$
NH_3	0	$2.35*10^{-3}$	$2.35*10^{-3}$

Emissions to air from heat power plant are allocated equally per MJ of electricity and heat. Most part of the carbon dioxide emitted during the operation phase of the heat power plant (use phase) is of biological origin. Thus, pertaining to the idea of biofuel cycle, carbon dioxide is not included in the assessment of environmental effects. Emission factors for laughing gas (N_2O) are results of personal communication with P-O Moberg at Birka Värme while factors for methane (CH_4) and ammonium (NH_4) are taken from Uppenberg et al. (1999).

11.3.3 Economy model

The cost for production of electricity and heat is shown Table 11.30.

Table 11.30 Costs of external production of heat and electricity

Fuel	Cost
Heat, biofuel	20.9 öre/kWh (Ericson, 1999)
Electricity, natural gas	57.6 öre/kWh (incl. tax for sulphur, CO_2, energy, electricity) (Ericson, 1999)

11.4 CHARACTERISATION FACTORS

11.4.1 Environmental characterisation factors

The environmental impact categories used to assess the output data from the ORWARE model are: greenhouse effect, acidification, eutrophication and photo oxidant formation. Furthermore energy and resource consumption in the form of primary energy carriers and metal flows are also assessed though not aggregated using characterisation factors.

The characterisation factors used are those recommended as the best available product specific environmental declarations of fuels in compilation of best available characterisation factors done by Uppenberg & Lindfors (1999. The factors are shown in Table 11.31.

Table 11.31 Characterisation factors

Emission	Global warming (kg CO_2-equivalents / kg emission)	Acidification (max) (kg SO_2-equivalents/kg emission)	Eutrophication (max) (kg O_2-consumption/kg emission)	Photo oxidant formation (kg O_3- equivalent /kg emission)
CO_2 (fossil) (air)	1	0	0	0
NO_x (air)	0	0.7	6	0.046
N_2O (air)	310	0	0	0
SO_2 (air)	0	1	0	0
CH_4 (air)	21	0	0	0.0006
CO (air)	0	0	0	0.003
NMVOC (air)	0	0	0	0.052
NH_3 (air)	0	1.88	16	0
HCl (air)	0	0.88	0	0
NH_4 (water)	0	0	15	0
NO_3 (water)	0	0	4.4	0
COD (water)	0	0	1	0
P (water)	0	0	140	0

For acidification and eutrophication, the maximum scenario is selected for the purpose of the study. This means nitrogen's contribution to acidification and eutrophication is accounted as maximum.

11.4.2 Economic weighting methods

The economic weights are obtained mainly from a Norwegian study, ECON 1995. As a complement to this study, Gren (1993) is used in case of eutrophication as shown below in Table 11.32. Table 11.33 shows the weighting factors based on Eco-tax from FMS (The Environmental Strategies Research Group) used in this study.

Table 11.32 Economic weighting factors in ORWARE'99

[SEK/kg]	Air emission	Water emission	Soil emission	Reference
CO_2 (fossil)	0.40	0	0	Econ (1995)
CH_4	8.40	0	0	Econ (1995)
VOC	1.49	0	0	Econ (1995)
CO	0.11	0	0	Econ (1995)
NH_3/NH_4	0.00	47	0	Gren (1993)
NO_x	54.00	0	0	Econ (1995)
N_2O	124.00	0	0	Econ (1995)
SO_x	34.01	0	0	Econ (1995)
P	439.00	439	0	Gren (1993)
Cl	68.00	0	0	Econ (1995)
Pb	310 000.00	310 000	310 000	Econ (1995)
Cd	1 123 000.00	1 123 000	1 123 000	Econ (1995)
Hg	232 000.00	232 000	232 000	Econ (1995)

Table 11.33 Economic weighting factors in Ecotax '99

[SEK/kg]	Air emission	Soil emission	Water emission
CH_4	8	0	0
VOC,	125	0	0
CHX satt.	94 800	96 000	36 000
AOX	94 800	96 000	0
PAH	684 000	336 000	85 200
Phenols	0	55	0
Dioxin	2 280 000 000	385 000 000	0
NH_3-N	34	12	0
NO_x-N	40	40	0
N_2O-N	115	0	0
S-tot	30	30	0
P-tot	0	84	0
Cl-tot	13	0	0
Pb	1 800	300	2 448
Cd	300 000	58 000	30 000
Hg	3 808 000	127 840	7 616 000
Cu	240 000	62 000	34 000
Cr	4 080 000	920	23 120
Ni	1 000 000	600 000	567 000
Zn	17 800	3 600	1 880
COD	0	1	0

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