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Resources, Conservation and Recycling 49 (2006) 68–88

Resources Conservation & Recycling

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Optimising waste treatment systems Part A: Methodology and technological data for optimising energy production and economic performance

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Received 18 August 2005; received in revised form 14 February 2006; accepted 3 March 2006
Available online 27 April 2006

Abstract

The treatment and utilisation of biomass residues and waste for energy and recycling can contribute significantly to greenhouse gas emission reduction. Therefore, a waste treatment structure should be designed for an efficient saving of fossil primary energy in terms of maximal primary energy savings or minimal costs per unit of primary energy savings. However, this is a complex task, given the large number of technologies, recycling options and their logistic consequences, that necessitate an integrated analysis. Also, on longer term various new and improved technologies become available which can affect performances for options from an economic and/or energy point of view. For that reason, an optimisation tool, that optimises a biomass and waste treatment system for a given amount of biomass and waste, is developed in this study. This optimal biomass and waste treatment system is composed of several treatment installations, that are characterised by scale, location and kind of technology. Important aspects that are taken into account in the analysis are heat distribution, biomass and waste transport and economies of scale. A broad variety of technologies for material recycling, conversion of biomass and/or waste to heat, electricity or transportation fuel are included in the optimisation tool. Performance data of these technologies are based on an extensive review. Examples

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DOI of the related article:10.1016/j.resconrec.2006.02.002

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doi:10.1016/j.resconrec.2006.03.004

of included technologies comprise: integrated gasification with combined cycle, waste incineration, pyrolysis, digestion, co-firing in fossil power plants, biomass incineration, hydro-thermal upgrading, paper recycling and chipboard production. A comparison of the different technologies in relation to scale shows that primary energy savings and costs per unit of primary energy savings diverge significantly. In general, the optimisation tool developed here is suitable for analyses of optimal biomass and waste treatment structures in different regions with regard to primary energy savings and their costs. By means of scenario analysis, robust optimal solutions in terms of primary energy savings and their costs can be identified and the influence of important parameters can be analysed. A case study of the Dutch biomass and waste treatment systems has been carried out with the optimisation tool and is presented in part two of this article.

Keywords: Solid waste; Recycling; Primary energy savings; Optimisation; Waste treatment; Biomass

1. Introduction

Considering the important role biomass residues and non-biomass wastes play in the agenda on greenhouse gas emission reduction, waste treatment and utilisation should contribute to the saving of fossil primary energy. Current waste treatment (in OECD countries) is characterised by landfilling, composting, incineration and to a lesser extent digestion. However, the design of a treatment infrastructure that is suitable for the efficient saving of primary energy—in terms of a maximum of savings at a minimum of costs—is a complex task.

First, many different technologies to utilise or treat biomass residues and municipal solid wastes are available or being developed. The options range from material reuse and recycling to the generation of heat and power and the production of liquid fuels.

Second, a number of variables influence the planning and arrangement of biomass and waste handling structures remarkably. These variables include the availability of biomass and wastes, the extent of waste separation, developments in conversion technologies and the kind of energy carriers or materials preferably produced from biomass waste. Scale effects play a significant role in the performance of such biomass and waste treatment systems. While many conversion technologies become more efficient with regard to energetic efficiencies and costs at larger capacity, the adverse happens with respect to energy use and costs of waste transport and heat distribution (Dornburg and Faaij, 2001a). As a consequence, the optimal scale of biomass and waste conversion installations depends on the technology used and the regional distribution of suitable biomass and waste streams.

Therefore, to identify optimal biomass and waste treatment strategies in terms of primary energy savings and their costs, an integral modelling taking all relevant parameters and technologies into account is necessary. A review of existing computer models and studies reveals that tools and approaches available do not analyse waste treatment in such an integrated manner; compare, e.g. Wang et al. (1998), Berger et al. (1998), Tellus Institute (1998), Feenstra et al. (1995), Sundberg (1997), Tanskanen (2000) and Holmgren and Henning (2004). For example, none of the models analyses indirect primary energy savings of recycling in an integrated way with heat, electricity or fuel production. (Nevertheless, certain aspects of the models reviewed are useful for the purpose of this study, e.g. logistic aspects or descriptions of waste conversion technologies.)

Therefore, in this study an optimisation tool is developed that can identify a future optimal waste treatment and utilisation strategy for a given amount of biomass and waste with regard to primary energy savings and their costs. The optimal capacity of a conversion installation in terms of costs and energy is one of the main questions tackled within this optimisation tool. As a consequence, economies of scale, transport and heat distribution are taken into account. Also a broad variety of technologies for the production of heat, power and materials are considered. The timeframe considered is the year 2020. (This article is part one of a series. In part two, a scenario analysis of the Dutch situation will be carried out with the optimisation tool described here.)

The procedures and calculation methodology of the developed optimisation tool are described in Section 2. Section 3 presents the input data of the optimisation tool, while in Section 4 the performance of the different biomass and waste treatment technologies in relation to scale is compared. Moreover, important break-even-points between technologies with regard to primary energy savings and market prices of recycling materials are discussed. Section 5 finishes with discussion and conclusions regarding: (1) the structure and abilities of the optimisation tool and (2) the comparison of different technologies to utilise or treat biomass and waste.

2. Optimisation tool

The optimisation tool identifies optimal utilisation and treatment for a given amount of biomass and waste for the year 2020. The tool has been used to analyse the utilisation and treatment of biomass and waste on a national level in the Netherlands by means of different scenarios. The results of that application are described in part 2 of this article.

2.1. Main structure

The main structure of the optimisation tool is presented in Fig. 1. The procedure starts from a set of input data containing the amount of biomass and waste available. First, it is assumed that separated non-combustible waste streams (iron, aluminium, glass and stony material) are recycled. Thus, the treatment of these wastes is independent of optimisation but energy savings and costs of recycling these streams are taken into account. Second, existing capacity to utilise waste and biomass can optionally be taken into account. If considered, the amount of biomass and waste for the following optimisation step is reduced by the full capacity of these existing installations.

The user selects the criterion for the optimisation procedure in advance. This criterion is either: (1) a maximal amount of fossil primary energy savings or (2) minimal costs per unit of fossil primary energy savings. After optimisation, a structure for the utilisation and treatment of the total amount of available biomass and waste results. This structure describes which streams are recycled, used in existing installations or converted to energy in new installations and the respective primary energy savings and costs. For the new installations

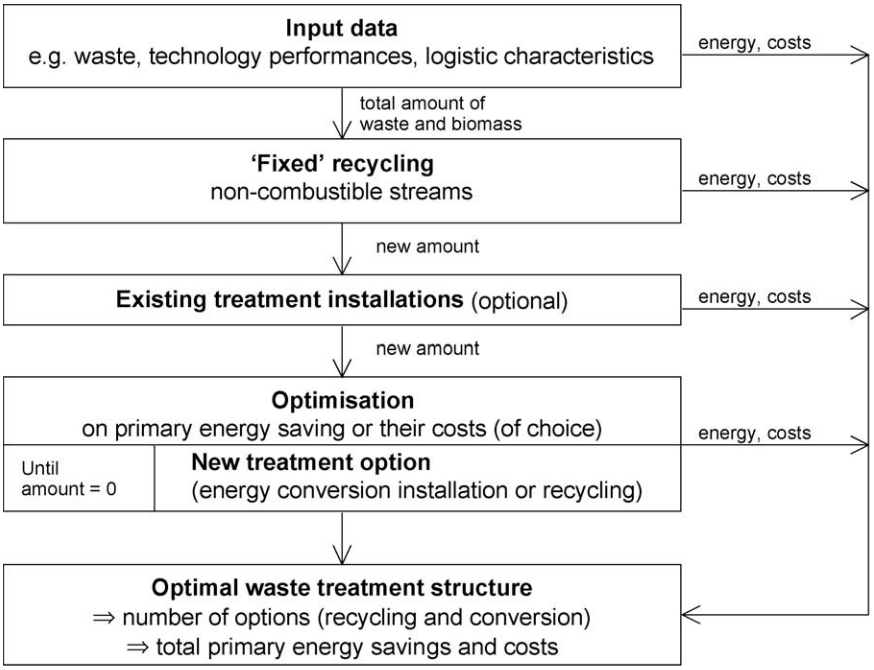

Fig. 1. Main structure of the optimisation tool.

for the conversion of biomass and waste to energy, moreover, capacity and location are calculated.[2]

Fig. 2 shows the actual optimisation procedure. First, scale and location of a possible new installation are selected. Next, the costs and the primary energy savings of all biomass and waste utilisation technologies are calculated for the selected scale and location. For this purpose, it is assumed that all possible biomass and waste streams are used by a technology.[3]

No results are calculated for a technology at the selected scale, if the scale is not applicable to a technology or the suitable amount of biomass and waste is insufficient. For recycling options, however, location and scale are fixed as it is assumed that recycling takes place in existing installations for (virgin) material production.

From the results, a preliminary best option is selected according to the optimisation criterion. Afterwards, scale and location are again varied and the costs and primary energy savings of installations are analysed. This variation of technology (t), location (l) and scale (s) determines the performances of all possible combinations. Subsequently, the best installation, i.e. a technology at a certain location and scale, is selected. For the remaining amount of biomass and waste, utilisation and treatment is optimised repeatedly until the total amount is used.

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[2] The location describes the spatial distribution of the waste treatment facilities. In the case study described in part 2 of this article, the provinces of the Netherlands have been used as unit for spatial distribution.

[3] To determine which waste streams can be treated by a certain technology the model relies on a matrix defining possible combinations; see Section 4.1.

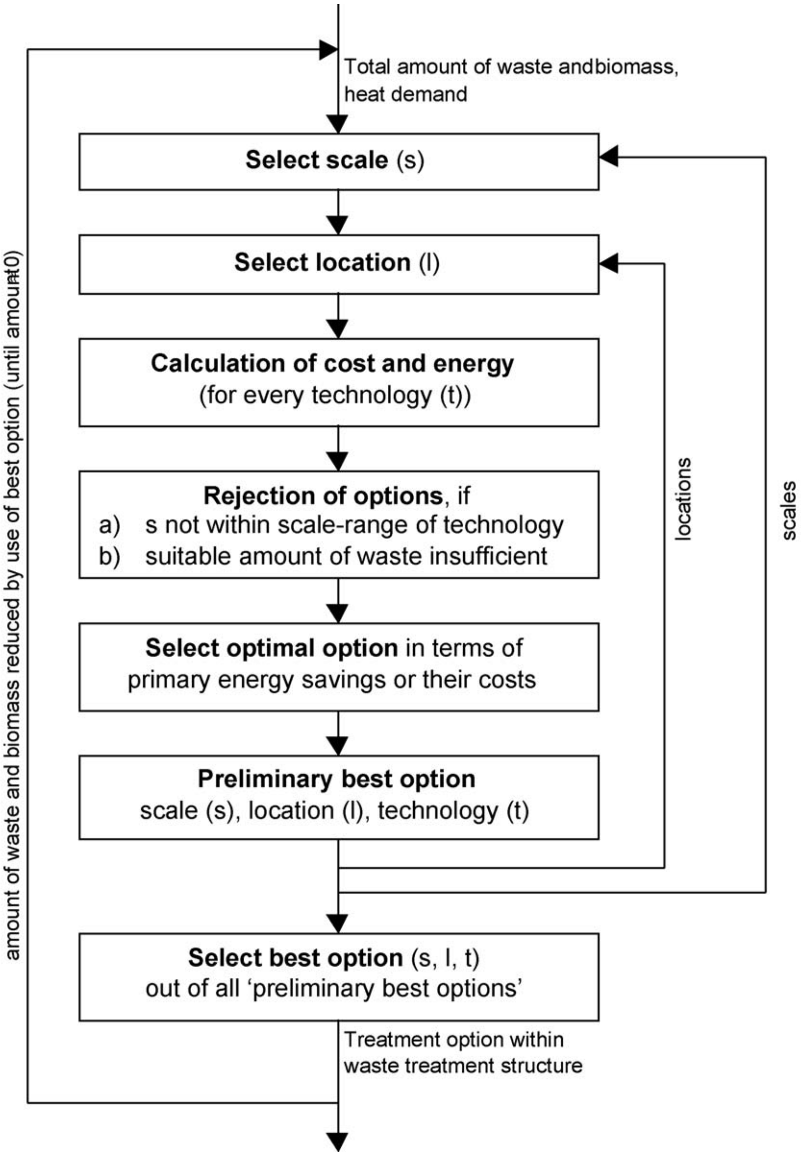

Fig. 2. Optimisation procedure.

2.2. Calculation method

For the optimisation, primary energy savings per energy input $\mathrm{PE}/\mathrm{PE}_\mathrm{w}$ and costs per primary energy savings *C*/PE of possible installations are calculated including conversion to energy or material recycling, transport and heat distribution; see formulae (1) and (2).

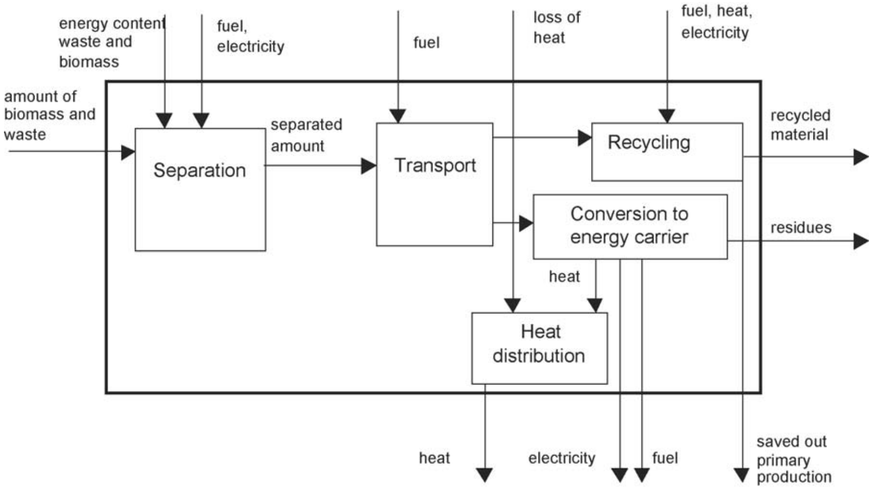

Fig. 3. Flows of material and energy within the biomass and waste treatment system.

Moreover, within the total waste treatment system an optional waste separation step can be included. Material and energy flows within the total biomass and waste treatment system are presented in Fig. 3.

$$\frac{\mathrm{PE}}{\mathrm{PE_w}} = \frac{\mathrm{PE_h} + \mathrm{PE_e} + \mathrm{PE_f} + \mathrm{PE_m} - \mathrm{PE_t} - \mathrm{PE_d}}{\mathrm{PE_w}} \tag{1}$$

$$\frac{C}{\mathrm{PE}} = \frac{-C_\mathrm{h} - C_\mathrm{e} - C_\mathrm{f} - C_\mathrm{m} + C_\mathrm{t} + C_\mathrm{d} + C_\mathrm{w} + C_\mathrm{c} + C_\mathrm{o}}{\mathrm{PE}} \tag{2}$$

where PE: primary energy saved or used [$\mathrm{MJ_p}$]; C: costs [€]; h: heat production; e: electricity production; f: fuel production; m: (secondary) material production; t: transport; d: heat distribution; w: input of waste and biomass used; C_c: capital costs of installation [€]; C_o: operational costs of installation [€].

2.3. Energy conversion

Energetic efficiencies of technologies determine the amount of heat, electricity or fuel that is produced within a conversion installation; see Section 3.1. Heat and electricity are converted to fossil primary energy savings by average projected efficiencies of fossil power plants in 2020. Fossil primary energy savings of transportation fuel are determined by the gross energy requirement of diesel fuel production; see Table 4. The energy carriers are sold for their respective market prices as forecasted for the year 2020. Thus, these revenues do not contain any subsidies or special tariffs for ‘green’ electricity. All economic calculations are thus based on costs.

2.4. Material recycling

The production of secondary materials by recycling mostly results in indirect savings of primary energy. These primary energy savings consist of the energy required to produce the substituted virgin materials, minus the energy used during recycling. Gross energy requirements (GER) values are used to express these primary energy requirements of material production.[4]

2.5. Transport

Starting point for the calculation of costs and energy uses of transportation is the spatial distribution of biomass and waste. Therefore, the level of detail of transportation is linked to the available data on waste distribution and to the available data on transport infrastructures. The optimisation tool then assigns suitable biomass and waste streams to a possible installation in order of distance from the location of the respective installation. This is done until the installation is supplied with biomass and waste for its full capacity. The transportation distance for biomass and waste is the average distance between the locations, i.e. a province in our case study, or the average distance within the area of a single location. Additionally, a transfer is taken into account, if biomass and waste are transported between different locations.[5] For recycling options that are not allocated to a specific location (see Section 2.1) an average transportation distance of waste is assumed. For transport of biomass and waste large trucks (full load, empty return) are assumed. Finally, primary energy uses and costs of transport are calculated from all transportation and transfer steps involved; see formulae (3) and (4).

This simplification of logistical issues is necessary due to the limited availability of data on the spatial distribution of biomass and waste for the case study performed in part 2 of this article. The influence of this simplification is discussed later. Nevertheless, the tool can easily be applied on spatially more detailed level when sufficient data are available as demonstrated in Meuleman and Faaij (1998).

$$\mathrm{PE}_{\mathrm{t}} = e_{\mathrm{t}} \times \left[\sum(m_{\mathrm{l}} \times s_{\mathrm{l}}) + m_0 \times s_0\right] + e_{\mathrm{tr}} \times \sum(m_{\mathrm{l}}) \tag{3}$$

$$C_{\mathrm{t}} = c_{\mathrm{t}} \times \left[\sum(m_{\mathrm{l}} \times s_{\mathrm{l}}) + m_0 \times s_0\right] + c_{\mathrm{tr}} \times \sum(m_{\mathrm{l}}) \tag{4}$$

where e: specific energy use; c: specific costs; $m_{\mathrm{l}:}$ used waste and biomass from province (l) [tonne]; $s_{\mathrm{l}:}$ distance of province (l) from the plant location province [km]; t: road transport; tr: transfer; m_0: used waste and biomass from the plant location province [tonne]; s_0: average distance in the plant location province [km].

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[4] Gross energy requirements comprise the energy content of the raw material and the energy that is used in the whole production chain. GER values are typically expressed as GJ/tonne of material; see Table 3.

[5] Collection of biomass and waste is not considered in the optimisation tool as it takes place independently from the kind of utilisation or treatment.

2.6. Heat distribution

Heat production is characterised by the scale and thermal efficiency of installations. The heat that is utilised, however, is also limited by heat demand and distribution. In the optimisation model, this amount depends on the optimisation criterion. Thus, either primary energy savings of heat utilisation are maximised or the costs per unit of primary energy saving are minimised.

The primary energy savings and costs of heat calculation are composed of the equivalents of heat delivered, the losses of power generation due to reduced electric efficiency and the heat losses during distribution. To determine impacts of heat distribution a constant heat demand per area representative for district heating in a built environment is assumed. Moreover, it is assumed that heat is transported over a marginal distribution distance that is the radius of the circle in which the total heat demand is located; see formulae (5) and (6).

$$\mathrm{PE}_{\mathrm{d}} = e_{\mathrm{d}} \times \frac{2}{3} \times [Q_{\mathrm{h}-}^{1.5} \times (D_{\mathrm{h}-} \times h_{\mathrm{h}} \times \pi)^{-0.5}] \tag{5}$$

$$C_{\mathrm{d}} = c_{\mathrm{d}} \times \frac{2}{3} \times [Q_{\mathrm{h}-}^{1.5} \times (D_{\mathrm{h}-} \times h_{\mathrm{h}} \times \pi)^{-0.5}] \tag{6}$$

where e_{d}: specific energy use of heat distribution [MJ/(MJ km)]; Q_{h}: amount of heat used [MJ]; h_{h}: operation time of heat production [s]; D_{h}: density of heat demand [MW/km^2]; c_{d}: specific costs of heat distribution [€/(MJ km)].

2.7. Capital and operation costs

For the installations that convert biomass or waste to energy, capital and operational costs are considered; see formula (2). The capital costs are derived from investment costs, the rent and the average lifetime of an installation; see Sections 3.1 and 3.2.

3. Input data

Input data for the optimisation tool can be divided into three categories. Data in *category I* describe the performance of biomass and waste utilisation and treatment technologies. These technology data consist of investment costs, operational costs, energetic efficiencies, load factors, characteristics of recycling and a matrix of possible combinations of biomass waste streams and technologies; see below.

Category II contains contextual data of the biomass and waste treatment and utilisation system. These data comprise market prices and primary energy equivalents of fossil energy carriers, specific costs and energy uses of transport, and specific costs and energy uses of heat distribution. In first instance, the values used for these parameters are representative for the Dutch context. However, all of these variables can be easily adapted to different locations and many of them are valid for other industrialised countries as well; see below.

Data in *Category III* are scenario-specific. These data include existing treatment capacities, availability of biomass and waste and their spatial distribution and heat demand. These are needed in the scenario analysis covered by part 2 of this article. For the case of the Netherlands, these scenario-specific data are also presented in part 2 of this article.

3.1. Technology selection

As it was beyond the scope of this study to cover all available and possible technologies, a set of representative technologies has been selected for inclusion in the optimisation tool.[6] The selected technologies represent technologies to convert biomass and waste to materials, heat, power or transportation fuels and include gasification, incineration, pyrolysis, co-firing, digestion and material recycling. For biomass and combustible waste these selected technologies are presented in Table 1. Material recycling technologies for the use of combustible waste are tyre recycling, chipboard production, use of organic wastes as cattle fodder or fertiliser, animal fodder production, mechanical and back-to-feedstock recycling of plastic and paper recycling. Moreover, non-combustible wastes for recycling comprise ferrous scrap, aluminium, glass and inert materials, i.e. stones, sand, ceramics, etc.

3.2. Combination matrix

Not every technology can be used for any type of waste. Therefore, a matrix of possible combinations of biomass and wastes with technologies in the optimisation tool is included; see Table 1. Generally, two different reasons lead to the exclusion of combinations. First, combinations that are technically not feasible are marked by blank box in Table 1. Second, combinations that lead to an inefficient use or conversion of a biomass or waste stream are indicated by a zero.

Most technological limitations to combine a conversion-to-energy-technology with a certain biomass or waste stream are due to the moisture content and/or the degree of contamination of the respective stream. Very wet streams, e.g. with more than 60% moisture content, cannot be gasified, combusted or pyrolised, and contaminated wastes cannot be treated with technologies that are not sufficiently equipped with (gas) cleaning capacity. For recycling applications, only few streams are suitable as quite specific characteristics and quality demands of the respective biomass or waste stream are required.

Limitations due to the sufficient use of the quality of a stream concern clean biomass, high-calorific wastes and separated wastes. Clean and relatively dry biomass as well as separated wastes are not combined with (low-efficient) technologies primarily designed for the combustion of wastes, e.g. mass burning. Also high-calorific wastes like plastics are not treated with technologies with relatively low energy efficiencies.

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[6] For the conversion of biomass and waste to energy, many comparable technological options exist of which representative technologies have been selected. For example, bubbling and circulating fluidised bed gasification are summarised as fluidised bed gasification as costs and energetic efficiencies are comparable. Also, CHP and power production at very small-scales of less than 3 $MW_{th\text{-}input}$ are not considered as an earlier analysis had already shown that these options save about 10% less fossil primary energy than small-scale heat production (Dornburg and Faaij, 2001a).

Table 1
Combinations of conversion-to-energy technologies with biomass and combustible waste streams

	Wood from fruit farming	Thinning, pruning	Straw	Hemp	Hay	Bulb cultivation	Greenhouse	Chicken manure	Verge grass	Food and beverage industry	Swill
FB gasification with gas engine	X	X	X	X	X			X			
Biomass integrated gasification combined cycle (BIG/CC)	X	X	X	X	X	X			X		
Integrated gasification combined cycle (IG/CC)	X	X	X	X	X	X		X	X		
Co-firing natural gas power plant with gasification	X	X	X	X	X	X		X	X		
Grate firing of waste	0	0	0	0	0	X		X	X	X	
CFB combustion of waste	0	0	0	0	0	X		X	X		
Co-firing coal power plant with pyrolysis	X	X	X	X	X	X		0	X		
Hydro-thermal upgrading with co-firing coal power plant			X	X	X	X	X	X	X	X	X
Digestion with gas engine			X	X	X	X	X		X	X	X
Co-firing coal power plant with gasification	X	X	X	X	X	X		X	X		
Indirect co-firing coal power plant	X	X	X	X	X	X		X	X		
Co-combustion cement kiln	0	0	0	0	0	X		X	X		
Biomass combustion, heat	X	X	X	X	X						
Biomass combustion, heat	X	X	X	X	X	X			X		
Fischer Tropsch	X	X	X	X	X	X		X	X		
Methanol synthesis	X	X	X	X	X	X		X	X		
Chipboard production	X	X									
Cattle fodder			X	X					X		
Fertiliser			X			X	X		X		
Animal fodder											X
Plastic recycling (material and back-to-feedstock)											
Paper production											
Tyre recycling											

Table 1 (*Continued*)

	Waste wood	Organic domestic waste	MSW	RDF (refuse derived fuel)	Shredded car wrecks	Sweepings	Tyres	Sewage sludge	Clean wood rests	Plastic	Paper
FB gasification with gas engine									X		
Biomass integrated gasification combined cycle (BIG/CC)									X		
Integrated gasification combined cycle (IG/CC)	X	0	X	X	X	X	X	X	X	X	X
Co-firing natural gas power plant with gasification		0	X	X	X	X	X	X	X	X	X
Grate firing of waste	X	0	X	X	X	X	0	X	0	0	0
CFB combustion of waste	X	0	X	X	X	X	X	X	0	0	0
Co-firing coal power plant with pyrolysis	X			0			X		X	X	0
Hydro-thermal upgrading with co-firing coal power plant		X						X			X
Digestion with gas engine		X									X
Co-firing coal power plant with gasification	X	0	X	X	X	X	X	X	X	X	X
Indirect co-firing coal power plant									X	X	X
Co-combustion cement kiln	X		X	0		X	X		0	X	0
Biomass combustion, heat									X		
Biomass combustion, heat									X		
Fischer Tropsch	X		X	X	X	X	X	X	X	X	X
Methanol synthesis	X		X	X	X	X	X	X	X	X	X
Chipboard production	X								X		
Cattle fodder											
Fertiliser											
Animal fodder											
Plastic recycling (material and back-to-feedstock)										X	
Paper production											X
Tyre recycling							X				

X: considered combination within optimisation tool. 0: technologically possible, but not considered combination.

3.3. Energy conversion technologies

Energy efficiencies as well as the investment costs of technologies to convert biomass and waste to energy depend on their capacity. Typically, efficiencies increase and investment costs per unit of installed capacity decrease with up-scaling. Efficiencies and specific investment costs, however, do not, respectively, increase or decrease to an unlimited extent. Instead these values approach a limit at large scales, while scale effects are more pronounced at smaller scales. Logarithmic curves or 'trendlines' can describe those scale effects.[7]

Efficiencies and investment costs of existing technologies in combination with projections on the technological developments within the next 20 years are the basis to set-up these trendlines by regression; see Table 2 for a detailed overview of datasets used. Here, also a realistic scale range that is considered in the optimisation tool is presented for each technology.[8] Finally, all investment costs of installations are converted into capital costs assuming a lifetime of 15 years and a rent of 6%.

3.4. Material recycling

Primary energy savings achieved by different types of material recycling are summarised in Table 3. On the one hand, these primary energy savings are well researched in case the materials are customarily recycled, i.e. ferrous scrap, aluminium, glass, paper and inert materials. On the other hand, primary energy savings are difficult to determine in case of inhomogeneous waste streams that have several possible recycling applications:

1. Primary energy savings of *plastic recycling* depend strongly on the composition of plastic waste as well as on the application of recycled material. Here, the average composition of separated plastics from German domestic wastes is assumed, as no data on the Dutch situation were available. Moreover, it is assumed that 65% of these plastic wastes is suitable for material recycling, i.e. producing the same type of plastic. The remaining plastic wastes are used for back-to-feedstock recycling, i.e. converted into oil.
2. For material *recycling of tyres*, two main processes exist, i.e. remoulding and production of rubber granules for tyre production. In this study, it was assumed that 33% of old tyres are remoulded[9] and the rest are reused as rubber granules.
3. Primary energy savings of *chipboard production* are equivalent to the energy content of the wood necessary for primary chipboard production.
4. For the use of hay and straw as *cattle fodder*, no data were available. Therefore, the gross energy requirement of hay is assumed to be equivalent to the primary energy saved.

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[7] Trendlines of efficiencies and investment costs can be composed by regression technique based on values observed in real plants and/or model calculations; see Dornburg and Faaij (2001a).

[8] Note that in this article scales are indicated in thermal capacity of biomass and waste input.

[9] It is technically feasible to remould about 38% of tyres depending on quality (Klootwijk et al., 1998).

Table 2

Characteristics of technologies to convert biomass and waste to energy[a]

	Electric efficiency[b]	Heat/fuel efficiency[c]	Investment costs[b] [€ 10^6 MW_{th-in}^{-}]	O & M costs [% of investment]	Load [h/year]	Scale [$MW_{th\text{-}in}$]
Electricity and heat production						
Fluidised bed gasification with gas engine	$0.016 \times \ln(P) + 0.270$	0.87	$-0.011 \times \ln(P) + 0.912$	6.5	5000	1–30
Biomass integrated gasification combined cycle (BIG/CC)	$0.045 \times \ln(P) + 0.312$	0.87	$-0.308 \times \ln(P) + 2.358$	6	8000	20–1000
Integrated gasification combined cycle (IG/CC)	$0.054 \times \ln(P) + 0.200$	0.87	$-0.212 \times \ln(P) + 1.803$	5	6500	20–1000
Co-firing natural gas power plant with gasification	0.50	0.8	$-0.070 \times \ln(P) + 1.157$	6	5000	20–1000
Grate firing of waste	0.29	0.77	$-0.624 \times \ln(P) + 5.297$	4	6500	50–1000
Circulating fluidised bed combustion of waste	0.29	0.77	$-0.561 \times \ln(P) + 4.77$	4	6500	50–1000
Co-firing coal power plant with pyrolysis	0.31	0.6	0.945	6	7000	400–1000
Hydro-thermal upgrading with co-firing coal plant	0.44	0.77	1.3	6	7000	100–1000
Digestion with combustion of biogas in gas engine[d]	0.13	0.13	1.3	16	8000	1–35
Co-firing coal power plant with gasification	0.35	0.38	0.82	10	7000	100–1000
Indirect co-firing coal power plant	0.395	0.40	0.512	10	7000	100–1000
Co-combustion cement kiln[e]	0	0.85	[d]	0	8000	1–50
Biomass combustion, heat only	0.0301	0.83	$-0.006 \times \ln(P) + 0.622$	6	≈Demand	1–20
Biomass combustion, combined heat and power	$0.022 \times \ln(P) + 0.206$	0.6	$-0.105 \times \ln(P) + 0.677$	4	8000	10–200
Fuel production						
Fischer Tropsch	0.047	0.46	$-0.175 \times \ln(P) + 1.781$	4	8000	100–1000
Methanol synthesis	0	0.56	$-0.159 \times \ln(P) + 1.503$	4	8000	80–1000

[a] Data are composed from literature data from: AOO (1998), Bestebroer et al. (1996), Bilitewski et al. (1994), van den Broek et al. (1995), Faaij et al. (1998b, 2000), FBT (1994), van Halen et al. (2000), Härdtlein and Kaltschmitt (1996), Heuvel and Stassen (1994), IEA (1998), Ising et al. (1998), Jahraus and Müh (1993), Kaltschmitt and Reinhardt (1997), Kaltschmitt et al. (1998), de Kant and Bodegom (2000), Pfeiffer et al. (1992), Rösch and Wintzer (1997), Solantausta et al. (1997), Tijmensen et al. (2002) and Veenendaal et al. (1994). For a more detailed description of data and references, see Dornburg and Faaij (2001b).

[b] P: scale of installation [$MW_{th\text{-}in}$].

[c] If optimisation assigns the use of heat to an installation, a deduction of electric capacity of $0.15\,MW_e/MW_{th}$ and an increase of specific investment costs of $€_{invest} 0.045 \times 10^6\ MW_{th}^{-1}$ are assumed (Dornburg and Faaij, 2001b).

[d] A revenue of $0.15\,GJ_{prim}/tonne_{waste}$ for the digestion residue which is used as fertiliser is taken into account (Faaij et al., 1998a).

[e] If waste is combusted in a cement kiln, 1 GJ of waste replaces about 0.8–0.9 GJ of fossil fuel (Wiegel et al., 1997). The costs are not calculated by investment costs, as cement kilns already exist in installations. Instead it is assumed that a fuel price of €1.5 GJ^{-1} allows for neutral waste incineration.

Table 3
Characteristics of recycling

	Market price (€/tonne)	Primary energy savings (GJ/tonne)
Non-combustible materials		
Ferrous scrap	45 (Vroonhof et al., 1994)	20 (Faaij et al., 1998a)
Aluminium	400 (Vroonhof et al., 1994)	188 (Faaij et al., 1998a)
Glass	9 (Vroonhof et al., 1994)	2.3 (Vroonhof et al., 1994)
Inert material (sand, etc.)	0 (Henkes, 1998)	0.1 (van Heijningen et al., 1992)
Sweepings	0 (estimate)	0.3 (calculation)
Combustible materials		
Tyre recycling	290 (RecycleNet, 2000)	60 (calculation)
Chipboard production[a]	45 (Bergsma and Sas, 1997)	16 (van Heijningen et al., 1992)
Cattle fodder use[b]	0 (estimate)	0.6 (Öko-Institut, 1999)
Fertiliser use[b]	0 (estimate)	0.2 (Faaij et al., 1998a)
Animal fodder production[b]	0 (estimate)	2.3 (Öko-Institut, 1999)
Plastic, material recycling[c]	120 (RecycleNet, 2000)	33.5 (Faaij et al., 1998a)
Plastic, back-to-feedstock	20 (RecycleNet, 2000)	16 (Faaij et al., 1998a)
Paper recycling	38 (Vroonhof et al., 1994)	21 (Henkes, 1998)

[a] It is expected that demand for waste wood and, thus, its price will rise in the near future. Therefore, the upper limit of what chipboard producers would be able to pay is used as market price.

[b] Organic wastes, which are applied in agriculture (fertiliser, fodder and animal food), often do not have an 'official' market value. Therefore, a zero price is assumed.

[c] The primary energy savings achieved by material recycling of different types plastics range from about 22 GJ/tonne (PVC) to 53 GJ/tonne (PUR).

5. Primary energy savings of *animal fodder* production are estimated by the gross energy requirement of pig fodder. However, no different nutrition values of swill and pig fodder could be taken into account due to a lack of data.
6. Primary energy savings of *fertiliser application* are based on the assumption that synthetically produced nutrients, i.e. potassium, phosphor and nitrogen, are replaced; see Faaij et al. (1998a).

Costs or profits of material recycling are based on the market prices of the respective waste materials; see Table 3. These market prices, however, depend strongly on quality and composition of the waste materials as well as on secondary material markets that are rather unstable. The market prices used in this study are based on the market situation in the year 2000. These market prices, however, can only give an indication of costs or benefits in the year 2020, as future developments are uncertain. Yet, an analysis of these developments is out of the scope of this study. The influence of these uncertainties is studied in a sensitivity analysis; see Section 4.

3.5. *Contextual data*

Market prices and primary energy uses of heat, electricity and fuel from fossil resources are presented in Table 4. Costs and primary energy uses of transportation and heat distribution are shown in Table 5. Main assumptions concerning these aspects were discussed in Section 2.

Table 4
Market prices and primary energy savings of fossil based energy carriers

	Market prices (€/GJ)	Primary energy savings (MJ_{prim}/MJ)
Electricity	9.1 (Dornburg and Faaij, 2001b)	1.93 (Fockens and Wijk, 1994)
Heat	4.9 (Dornburg and Faaij, 2001b)	1.05 (Fockens and Wijk, 1994)
Fuel	3.8[a] (Tijmensen et al., 2002)	1.03 (Sas, 1994)

[a] Because fuel prices fluctuate strongly in the world market, no reliable prognosis exists. Therefore, an actual price of about €3.8 GJ^{-1} is assumed.

Table 5
Cost and energy use of transportation and heat distribution

	Transport[a]	Transfer	Heat distribution
Costs	€5.79 × $s^{-0.64}$ $(\text{tonne km})^{-1}$[b] (Rösch and Kaltschmitt, 1998)	€0.28 tonne^{-1} (Meuleman and Faaij, 1998)	€64.38 $(\text{GJ km})^{-1}$ (Ossebaard et al., 1994)
Energy use	0.81 MJ_{prim}/(tonne km) (Kaltschmitt and Reinhardt, 1997)	0.47 MJ_{prim}/tonne (Faaij et al., 1998b)	0.08 × $P^{-0.49}$ km^{-1}[c] (Ossebaard et al., 1994)

[a] Assumed are large trucks of about 28 tonne payload (full load, empty return).

[b] s: distance [km].

[c] P: capacity [MW_{th}].

4. Performance of technologies

4.1. Costs and primary energy savings in relation to scale

In this section, the performance of the different technologies to treat and utilise biomass and waste in terms of primary energy saving per lower heating value input and costs per primary energy savings are compared; see Figs. 4 and 5. To determine these parameters in relation to scale, a spatial distribution of biomass and waste with an average density of about 1200 tonne/km^2 is assumed. This distribution is taken from a case study of the Netherlands (cf. part 2 of this article). Transport of biomass and waste is then included in the analysis as described in Section 2.

The costs per unit of primary energy savings differ significantly between the technologies. The highest costs are about €47 GJ_p^{-1} for digestion (which is outside the range of Fig. 4) and the lowest costs are about € − 4 GJ_p^{-1} for the recycling of waste tyres. Besides tyre recycling, the most interesting options are (biomass) integrated gasification with combined cycle (BIG/CC and IG/CC) with costs of about € − 1 GJ_p^{-1} (at capacities of about 800 $MW_{th\text{-}input}$). Also chipboard production, cattle fodder use, fertiliser use and paper recycling that all have costs of about €0 GJ_p^{-1} are attractive.

The primary energy savings per lower heating value input of the different technologies also show a broad range from 0% to 209%. The best options with regard to relative primary energy savings are paper recycling (209%), waste tyre recycling (166%) and chipboard production (140%). Besides, relative primary energy savings of a couple of technologies are in the range of 95–120%. These technologies are (B)IG/CC, co-firing in natural gas combined cycle plants, recycling of plastics and animal fodder production.

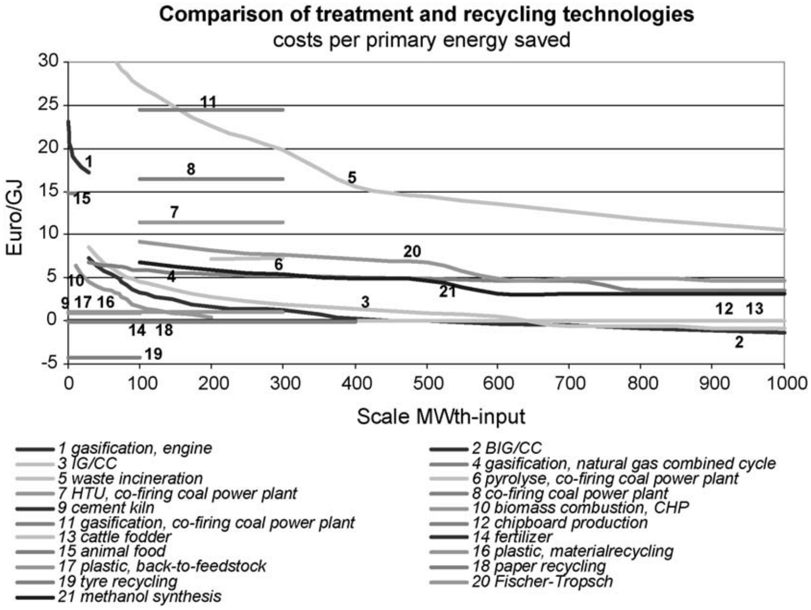

Fig. 4. Costs per primary energy saved of all treatment options in relation to scale.

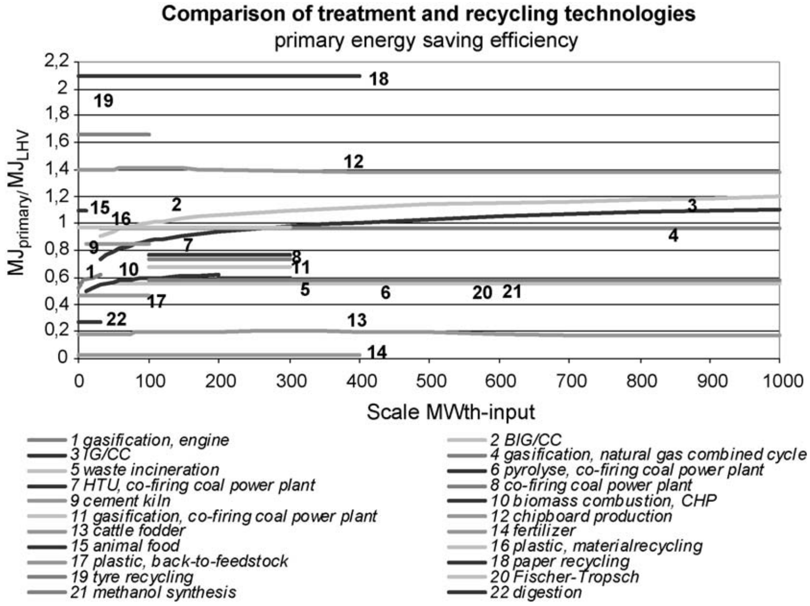

Fig. 5. Primary energy saving efficiency of all treatment options in relation to scale.

The steps in the curves in Fig. 4 are caused by transportation losses, as transport distances are discontinuous within the model. However, the influence of transportation on primary energy savings is small—less than 1% of primary energy savings—and, therefore, hardly visible in Fig. 5. This implies that in general it can pay off to transport waste over larger distances to convert it in bigger and, thus, more efficient units. This is especially true for combustion and gasification.

4.2. Break-even-points

Market prices of electricity, fuel and recycling material determine for a large part the economic performance of a technology for the utilisation and treatment of biomass and waste. These market prices, however, are subject to uncertain changes in the next 20 years. Primary energy savings achieved by fuel, electricity and material production influence as well for a large part the energetic performance of a technology. Nevertheless, also the primary energy savings of recycling materials vary with the reference system assumed. To investigate the influence of these uncertainties on technology selection, break-even-points between technologies with regard to market prices and primary energy savings of products have been analysed.

Market prices of electricity and fuel are set at default values of €0.0326 $\mathrm{kWh_e^{-1}}$ and €3.8 $\mathrm{GJ_{fuel}^{-1}}$ within the optimisation tool. With regard to costs per primary energy savings, fuel production, i.e. methanol synthesis, could compete with the cheapest option of electricity production starting from a fuel price of about €8.3 $\mathrm{GJ^{-1}}$. If electricity prices would increase to a ‘green’ electricity price of €0.0635 $\mathrm{kWh^{-1}}$,[10] a fuel price of €10.7 $\mathrm{GJ^{-1}}$ would be necessary to render fuel production competitive with electricity production.

The market price of wood for chipboard production is €45 $\mathrm{Mg^{-1}}$ in the optimisation tool, which is about the current upper limit of the chipboard industry’s raw material cost. However, chipboard production would just become more attractive than treatment of wood in a BIG/CC in terms of costs per primary energy savings, if this market price would increase to €95 $\mathrm{Mg^{-1}}$ (or even €166 $\mathrm{Mg^{-1}}$ in the case of a ‘green’ electricity price of €0.0635 $\mathrm{kWh^{-1}}$).

With the assumed market price of waste paper of €38 $\mathrm{Mg^{-1}}$, paper recycling cannot compete with electricity production from paper in an IG/CC in terms of costs per unit of primary energy savings. This would only be possible with a waste paper price of €72 $\mathrm{Mg^{-1}}$ (or €165 $\mathrm{Mg^{-1}}$ in the case of a ‘green’ electricity price).

With regard to primary energy savings, chipboard production from woody wastes is slightly favourable to electricity production. This would change, if primary energy savings of chipboard production would be 13.6 GJ/Mg instead of the baseline assumption of 16 GJ/Mg.

In contrast, with the reference value of 21 GJ/Mg primary energy savings, paper recycling is superior to electricity production. Just if reference systems are changed such as merely 12 GJ/Mg is attributed to paper recycling, electricity production becomes more favourable in terms of primary energy savings.

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[10] This is an estimate of international green electricity certificates (Tellus Institute, 1998).

Finally, the treatment of plastics in an IG/CC installation is more efficient than material recycling. This result is based on primary energy savings of 33.5 GJ/Mg for granulating mixed plastics. Though, if material recycling of plastics would only save 39.5 GJ/Mg of primary energy—this is within the range of figures for different sorts of plastic—recycling would be more attractive than gasification in an IG/CC installation.

5. Discussion and conclusions

5.1. Potentials of the optimisation tool

The developed optimisation tool is able to select an optimal—in terms of primary energy savings and their costs—biomass and waste treatment structure for a given area in the mid-term future. Integrated in the optimisation tool is a very broad range of technologies. These comprise many options for material recycling and the conversion of biomass and waste to energy. Furthermore, heat distribution and biomass and waste transportation are taken into account and existing waste treatment/conversion capacity can be included.

The optimisation tool is suitable for scenario analyses of biomass and waste treatment on a national or more local level. Thus, it allows for complex sensitivity analyses to evaluate the impact of different options.

5.2. Limitations of the optimisation tool

Within the optimisation tool, logistics are simplified. The collection of biomass and waste is not regarded and transport distances and transfers are estimated from average regional values. However, including collection of biomass and waste would not change the comparison of different technologies, and the method to estimate transportation distances can sufficiently approach the effects of logistics for the available data on spatial distribution of biomass and waste.

Heat demand is simplified in the optimisation, too. An average heat demand per area is assumed, while in reality heat demands can vary considerably between specific locations. Consequently, location selection in the optimisation tool is not specific with regard to heat demand, though it would be possible to determine optimal locations on a smaller aggregation level using a more detailed dataset on spatial heat demands.

Data on the performance of different waste treatment technologies influence the selection of technologies strongly. Performance data of pyrolysis, HTU, co-firing in coal power plants, fuel production and fluidised bed combustion of wastes are derived from only a few references. However, a range of values could be determined that allows for an estimation of the performance of these technologies.

Furthermore, materials' prices and to a lesser extent primary energy savings of recycling are uncertain, because dynamics of applications and prices in time are not well understood. This aspect deserves further study.

Finally, only a limited number of fuel production possibilities are taken into account in this study, even though a lot of technological development is going on in this field that could improve the performance of biofuel production considerably. Therefore, it would be advisable to pay more attention to these potential developments.

5.3. Comparison of technologies

The technologies considered vary significantly with regard to relative primary energy saving and cost per unit of primary energy savings. Therefore, increasing the economic and energetic efficiency of saving primary energy with waste and biomass treatment and utilisation requires a careful design of future waste management structures. Especially, an integrated analysis of recycling and conversion to energy technologies seems necessary.

Comparing relative primary energy savings, paper recycling, tyre recycling and chipboard production are the technologies options that perform best. These options are followed by conversion-to-energy technologies using a combined cycle for electricity production. However, R&D efforts to further develop these technologies are still necessary in order to achieve the performances assumed in this study. In relation to costs per primary energy savings the comparison of technologies is less evident as technology selection is rather sensitive to variation of market prices as demonstrated in the analysis of break-even-points.

Acknowledgement

We would like to thank the Ministry of Housing, Spatial Planning and the Environment for financial support of this study.

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