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Resources, Conservation and Recycling 48 (2006) 227–248
Resources Conservation & Recycling
www.elsevier.com/locate/resconrec

Optimising waste treatment systems Part B: Analyses and scenarios for The Netherlands

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Received 18 August 2005; accepted 1 February 2006
Available online 29 March 2006

Abstract

Material recycling as well as energetic production of biomass residues and other solid wastes could significantly contribute to fossil primary energy savings. Waste treatment should, therefore, aim to combine pollution abatement with the efficient saving of fossil primary energy. This article *identifies optimal waste treatment strategies* in The Netherlands. Here, an optimal strategy is one that either maximises the fossil primary energy savings or minimises the costs per unit of fossil primary energy savings that are achieved by the utilisation of available biomass residues and wastes. Also, the influence of different factors – for example, the availability of wastes or technological developments – on the robustness of technological options and on the variation of costs and fossil primary energy savings is studied. With a specially developed optimisation tool (described in Part I of this article series) several variants of Dutch waste treatment systems ('scenarios') are analysed by back casting to the year 2020. This tool allows for quick analyses of complete waste treatment infrastructures. The results show that the objective of the Dutch government to supply 120 PJ of primary energy demand in 2020 from biomass and waste seems more than feasible, while in 2000 about 43 PJ were realised. Including material recycling up to 437 PJ primary energy could be saved with an optimised waste treatment infrastructure. Choices made about alternative waste treatment strategies influence the costs strongly. Total costs for the Dutch waste treatment system – not considering revenues from waste treatment tariffs – vary from revenues of €230 million/year to costs of €820 million/year.

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0921-3449/$ – see front matter
doi:10.1016/j.resconrec.2006.02.002

The contributions of material and energy recycling to avoid primary energy use change significantly under different preconditions. In the 11 different scenarios considered, of the primary energy savings achieved 25–76% resulted from material recycling, 20–80% from heat and electricity production, and a more modest 0–21% from the production of transport fuel. (Biomass) integrated gasification with combined cycle, hydro-thermal upgrading and waste separation emerge as key technologies from this study, while for example, waste incineration and biomass co-firing in coal power plants do not come out as most attractive options for the longer term. Generally, large-scale conversion units seem favourable to achieve better economies and energy recovery.

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

1. Introduction

Currently, biomass and waste are widely recognised as important sources of sustainable energy. The Dutch government, for example, aims to supply 4.4% or 120 PJ of the national energy demand in 2020 from these resources by the generation of heat and power, while in 2000 about 43 PJ were realised (Joosen et al., 2001). Recently, also the production of transportation fuels from biomass has been acknowledged as valuable strategy for sustainable energy supply, for example a recent EU directive aims to supply 5.75% of transportation fuels by biofuels in 2010 (EU, 2003). However, the indirect saving of fossil fuels by means of recycling has not been explicitly established by policy goals (as in most EU countries), while nevertheless it could contribute significantly to the saving of fossil primary energy; see e.g. Faaij (2006).

Thus, considering the important potential role biomass residues and wastes can and do play in fossil primary energy savings, waste treatment should combine pollution abatement with efficient saving of fossil primary energy (in terms of energy and costs). However, most modern waste treatment systems – including the Dutch national system – aim to treat wastes as ‘cleanly’ as possible and are designed according to the priority list of: (1) avoidance, (2) recycling, (3) conversion to energy and (4) land-filling. Moreover, modern waste treatment systems rely on land-filling, composting, incineration and to a lesser extent digestion, which does not necessarily lead to save primary energy efficiently. An earlier – but rather crude – analysis of the Dutch final waste treatment system has shown, that savings of fossil primary energy use by waste treatment and recycling could be very significant and much higher than in the current situation (Faaij et al., 1998).

Therefore, this study aims at *identifying optimal biomass and waste treatment strategies for The Netherlands in order to save primary energy efficiently with regard to energy and costs*. Several key aspects are taken into account, for example varying waste supply, performance data for new and improved technologies, the comparison of heat and power generation with fuel production and material recycling, and changing performances at different scales. The treatment of (1) wastes similar to municipal solid waste and (2) biomass residues, i.e. organic wastes from the agro-forestry sector, is explicitly included. This article is Part II of a series in which the future Dutch waste treatment system is analysed by means of scenario analysis. This analysis is performed with an optimisation tool developed for this purpose. This tool and its input data are described in Part I of the article series; see (Dornburg et al., 2006).

In Section 2, the approach, the scenarioans and the input data are discussed. In Section 3, the optimal waste treatment structures resulting from the scenario analysis are presented. Sections 4 and 5 finish with discussion and conclusions.

2. Scenario analysis

2.1. Approach

To determine optimal waste management structures for The Netherlands on a national level, a scenario analysis is carried out. The scenarios consider potential future situations in 2020 and can be used for back casting exercises. This is in contrast to forecasting scenarios that explicitly start with the existing situation. Here, optimal means either the *maximal amount of primary energy savings* or *the minimal costs per unit of primary energy savings*.

For the year 2020 scenarios that assume different developments in the waste management sector (e.g. assuming a focus on integrated separation, slow technology developments, different amounts of waste) are defined. For each scenario an optimal waste treatment strategy is determined resulting in an allocation of various recycling/conversion technologies to each biomass and waste stream. Costs and fossil primary energy savings of each of these technologies are determined. Moreover, the scale and – in a crude way on a provincial level – the location of the waste treatment installations are optimised. Thus, the scenario analyses key technologies and variations of costs and fossil primary energy savings of waste treatment strategies. For these scenario analyses, an optimisation tool is used; see Part I of this article.

2.2. Input data

First, input data for the analysis are technology related data, i.e. on recycling processes,[1] biomass and waste treatment technologies,[2] heat distribution and transportation. These data are specified in Part I of this article. Second, input data are *site-specific data* for The Netherlands, e.g. the amount of waste and its spatial distribution, are described below.

The *available amounts* of biomass and waste are derived from available projections on the future waste and residue production in The Netherlands in 2020 (Zeevalkink and Koppejan, 2000). The spatial distribution of this waste is characterised by the 12 Dutch

[1] Recycling options within the model are: wood panel production; the use of agricultural waste as fertiliser or cattle fodder; production of animal food; material use or 'back to feedstock' use of plastic waste; paper recycling and tyre recycling.

[2] Possible waste treatment technologies are gasification coupled with a gas engine, a combined cycle, a natural gas combined cycle plant or with a coal-fired power plant; waste incineration; biomass combustion; co-combustion in a coal-fired power plant either directly or after gasification, pyrolysis or hydro-thermal upgrading; digestion; methanol production and Fischer-Tropsch synthesis.

provinces.[3] Energy contents of wastes are given by lower heating values. Regarding costs, market prices of waste streams that are currently positive are taken into account. For waste streams that currently have a negative market price, a price of zero plus transport costs is assumed, because these prices are likely to increase in the future, e.g. due to enlarged treatment capacity. Input data related to available biomass and waste streams are presented in Table 1.

For the *utilisation of heat*, district heating is regarded. The heat demand is characterised by a 'density' of 12 MW/km^2 (Ossebaard et al., 1994) and a load of 2500 h/year. This refers to an average future heat demand for district heating in an area with multi-storey buildings and one-family dwellings in The Netherlands.[4]

Existing capacity is considered in the analysis as well. Some of the co-firing options in fossil power plants and cement kilns (cf. Part I of this article) are limited to the plant capacity that will be installed in The Netherlands in 2020. For coal-fired power plants, it is assumed that no new capacity is installed and that depreciated installations are shut down. Thus, considering co-firing of 20% biomass, the capacity of co-firing in coal power plants is limited to 600 $MW_{th\text{-}input}$. Contrary, it is assumed that new natural gas power plants are built which can be used for co-firing using gasification; the fuel gas then replaces natural gas (Rodrigues et al., 2003). The presumably installed capacity in 2020 could treat about 80% of the total amount of biomass and waste at a 10% co-firing rate. Therefore, no upper limit for co-firing in natural gas plants is handled in this analysis. Co-firing capacity in cement kilns is limited to the current capacity of Dutch cement kilns, i.e. 100 $MW_{th\text{-}input}$.

2.3. Scenarios

The scenarios represent imaginable waste treatment situations in the year 2020 under varying circumstances. In this section, the characteristics of the scenarios are described; see also Table 2. If not stated otherwise, the scenarios are optimised for fossil primary energy savings.

The reference scenarios assume a business-as-usual development. Available amounts of biomass and waste correspond to predictions, separate waste collection is in accordance with current policy and heat demands represent average demands in the built-environment. Existing installations for the treatment of biomass and waste are depreciated and, consequently, no existing treatment capacity is considered for the year 2020. Technology developments of biomass and waste treatment installations follow average expectations. The two reference scenarios are *optimised for fossil primary energy savings and costs per unit of fossil primary energy saved*. Other scenarios are variations of these reference scenarios.

In the *separation scenario*, recycling is increased by large-scale application of integrated separation of wastes. Waste is collected separately to the same degree as in the reference scenario. Additionally, 'mixed' waste streams, i.e. domestic waste, bulk waste, commercial

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[3] In cases data is available on an national level only, the distribution of waste over provinces is estimated by means of general statistical characteristics of population, industry and agricultural structure. Average distance of the provinces to each other is about 170 km.

[4] Heat demands range from 5 MW/km^2 as future demand in 2010 in rural areas to 27 MW/km^2 in multi-storey buildings in 1993 (Ossebaard et al., 1994).

Table 1
Availability of biomass and waste streams within scenario-analyses for The Netherlands

Biomass and waste[a]	Cost (€/tonnes)	LHV[b] (GJ/tonnes)	Amount 'business as usual' (ktonnes)	Amount waste availability scenario (ktonnes)
Biomass				
Wood from fruit farming.	0	10.2	294	294
Thinning, pruning	0	10.2	1700	1700
Straw	100	13.5	723	723
Hemp	0	11.3	5	5
Hay	64	12.7	138	138
Bulb cultivation	0	5.0	75	75
Greenhouse waste	0	2.0	100	100
Chicken manure	0	6.6	2461	2461
Verge grass	0	5.0	468	468
Food and beverage industry	14	2.7	9564	9564
Swill	0	2.0	216	216
Clean wood rests	0	15.6	600	600
Combustible waste[c]				
Waste wood	11	15.4	1005	1390
Organic domestic waste	0	4.0	2655	2222
MSW	0	7.1	8097	12755
Plastic	0	34.4	426	629
Paper/cardboard	0	10.0	4119	4244
Shredded car wrecks	0	15.7	143	143
Sweepings	0	7.5	437	230
Tyres	0	36.0	103	103
Sewage sludge (25% ds)[d]	0	1.5	1604	1604
Non-combustibles				
Ferro	0	0	1202	1723
Non-Ferro	0	0	176	266
Glass	0	0	690	704
Stone, sand, etc.	0	0	10627	18852
Inert sweeping parts	0	0	706	770
Total			48334 (≅237 PJ)	61979 (≅284 PJ)

[a] Data on wastes from bulb cultivation and greenhouses (Faaij et al., 1998). All other data (Zeevalkink and Koppejan, 2000).

[b] Heating values from MSW and sweepings are calculated from their composition. In the separation scenario the LHV of MSW is 5.6 GJ/tonnes and the LHV of RDF is 15.0 GJ/tonnes.

[c] The plastic, paper and non-combustible fractions consist of separately collected wastes.

[d] If sewage sludge is gasified, it is dried prior to treatment to 85% d.m. Additional costs and energy use of this drying step are 32.1 €/tonnes$_{25\%\text{d.m.}}$ (Klootwijk et al., 1998) and 250 MJ/tonnes$_{25\%\text{d.m.}}$ (Houtman, 1997).

and industrial waste and construction waste are separated after collection. This separation produces recyclable materials and a high calorific fraction, i.e. residue derived fuels (RDF).

In the *no heat scenario*, it is assumed that (waste) heat cannot be utilised. This situation is considered, because decreasing heat demands and cheap alternatives, e.g. natural gas, might prevent the utilisation of heat from biomass and waste.

Table 2
Scenarios that were studied with the optimisation model

	Scenario	Waste	Heat demand	Technologies	Existing capacity	Optimum
1	Reference, energy	BAU[a]	BAU	No limitation	None	Fossil primary energy savings
2	Reference, costs	BAU	BAU	No limitation	None	Costs per f.p. energy savings
3	Separation	BAU + separation	BAU	No limitation	None	Fossil primary energy savings
4	No heat	BAU	0	No limitation	None	Fossil primary energy savings
5	Unlimited heat	BAU	∞	No limitation	None	Fossil primary energy savings
6	Backlash technology development, energy	BAU	BAU	(B)IG/CC worse, no HTU	None	Fossil primary energy savings
7	Backlash technology development., costs	BAU	BAU	(B)IG/CC worse, no HTU	None	Costs per f.p. energy savings
8	Maximal electricity and heat production	BAU	BAU	No recycling, fuel of combustibles	None	Fossil primary energy savings
9	Maximal fuel production	BAU	BAU	No electricity/heat from wastes suitable for fuel production	None	Fossil primary energy savings
10	Existing capacity	BAU	BAU	No limitation	Planned	Fossil primary energy savings
11	Waste availability	Prediction LAP[b]	BAU	No limitation	None	Fossil primary energy savings

[a] Business as usual.
[b] LAP,: Landelijk Afval Beheers Plan (National Waste Treatment Plan).

In contrast, in the *unlimited heat scenario* there is no threshold for heat utilisation and neither energy losses nor costs are limiting factors for heat distribution. Such a situation might be possible, if waste treatment facilities can be located structurally in the vicinity of greenhouses, new built-on areas and industrial sites. Thus, the maximal contribution of combined heat and power (CHP) production from biomass and waste to fossil primary energy savings can be determined.

The *backlash technology development scenario* examines the consequences of disappointing technology development in particular for (B)IG/CC[5] and HTU[6] technology. In the reference scenarios, technological developments of waste treatment technologies are presumed for the year 2020. These advances are particularly large for technologies that are still under development, such as gasification and hydro-thermal upgrading (cf. Part I of this article). However, these developments cannot be taken for granted. In this scenario, (B)IG/CC technology will not reach the predicted high electrical performance and low costs

[5] (Biomass) integrated gasification with combined cycle.
[6] Hydro-thermal upgrading.

and HTU technology will not reach maturity and, therefore, is assumed to be unavailable until 2020. The backlash technology development scenario is optimised on fossil primary energy savings and on costs per unit of fossil primary energy saved.

In the *maximal electricity and heat production scenario*, recycling of combustible streams and transportation fuel production from biomass and waste are excluded. This scenario reflects the consequences of a possible national policy that favours heat and power production in order to increase the amount of energy supplied from biomass and waste.

The *maximal fuel production scenario* examines the consequences of another possible priority of policy, i.e. the production of transportation fuel from biomass and waste. In this scenario, streams that are suitable for fuel production, i.e. relatively dry (60% moisture) combustible wastes, are not allowed for the production of heat and power.

The *existing capacity scenario* takes into account that some biomass and waste treatment installations are still in use in the year 2020. It is assumed that installations, that are currently planned or under construction, will still be operating. (This is a capacity of about 340 $MW_{th\text{-}input}$ for biomass co-combustion and about 220 $MW_{th\text{-}input}$ for waste incineration and pyrolysis.)

In the *waste availability scenario*, the amount of available wastes is higher than in the reference scenario. The assumed amount has been predicted in the development of a new Dutch national waste management programme (VROM, 2003). This scenario demonstrates the implications of generally uncertain predictions of waste availability, because these depend on many factors like economic growth, population growth as well as various policies.

2.3.1. Scenario-specific data

In the *separation scenario* (var. 3) it is assumed that waste is separated in an integrated waste separation plant. Separation rates of this technology are about 80% of organic wastes, 30% of paper and cardboard, 95% of ferrous material, 70% of non-ferrous metals, 80% of glass and 70% of inert materials (Sas, 1994). The changed waste availability after separation are presented in Table 3. Costs and energy use of the separation are about €27 $tonnes_{input}^{-1}$ and 0.26 GJ/$tonnes_{input}$ (Faaij et al., 1998).

Table 3
Changed waste availability after separation according to (Sas, 1994)

	Amount of waste (ktonnes)	
	Separation scenario	Reference scenario
Organic domestic waste	3971	2655
Plastic	426	426
Paper cardboard	4343	4119
Ferro	1403	1202
Non-ferro	202	176
Glass	782	690
Other combustibles	–	–
Stone, ceramic, etc.	11965	10627
Municipal solid waste	2449	8097
Residue derived fuel	2451	0

Table 4
Investment costs and efficiencies of (B)IG/CC technology in the backlash technology development scenarios (van Halen et al., 2000)

Parameter	(B)IG/CC	IG/CC
η_e as function of $MW_{th\text{-input}}$ (P)	$0.0105 \times \ln(P) + 0.443$	$0.0278 \times \ln(P) + 0.313$
Reference data	30 MW_e: $\eta_e = 0.48$, 50–150 MW_e: $\eta_e = 0.5$	Same reduction compared to BIG/CC as in reference scenario
Investment as function of $MW_{th\text{-input}}$ (P)	$-0.1258 \times \ln(P) + 1.586$ [10^6 €/MW_{th}]	$-0.1522 \times \ln(P) + 1.728$ [10^6 €/MW_{th}]
Reference data	30 MW_e: €5.29 million, 50–150 MW_e: $\eta_e = 0.5$ €3.12 million	Compared to BIG/CC same reduction as in reference scenario

In the *backlash technology development scenario* (var. 6 and 7), HTU is not available as a waste treatment technology and (B)IG/CC technology performs worse than predicted in the reference scenario. Instead electrical efficiency and investment costs of (B)IG/CCs reach a level of technology development based on pessimistic assumptions; see Table 4.

In the *waste availability scenario* (var. 11) the amount of biomass and wastes follows projections from the Dutch national waste management programme for the year 2011. The growth of waste production is extrapolated linear till 2020, while it was assumed that the recycling percentages reached in 2011 remain stable. The main differences of these projections from the projections in the reference scenario are higher rates of waste production and separate collection.

3. Results

An overview of the primary energy savings and the total costs in the different scenarios is presented in Figs. 1 and 2. Below, the main results for each scenario are discussed. For the reference scenario and the backlash technology scenario, results are also presented in

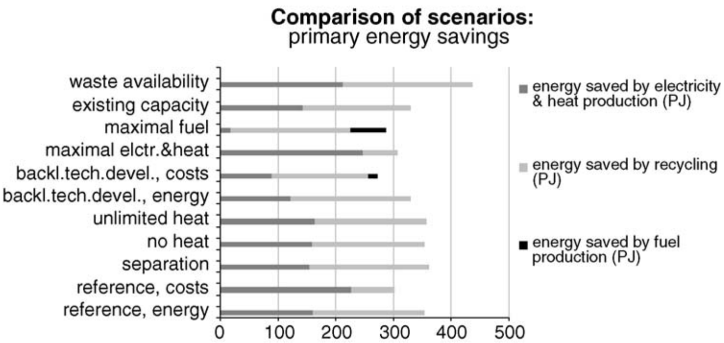

Fig. 1. Comparison of energetic performance of the different scenarios.

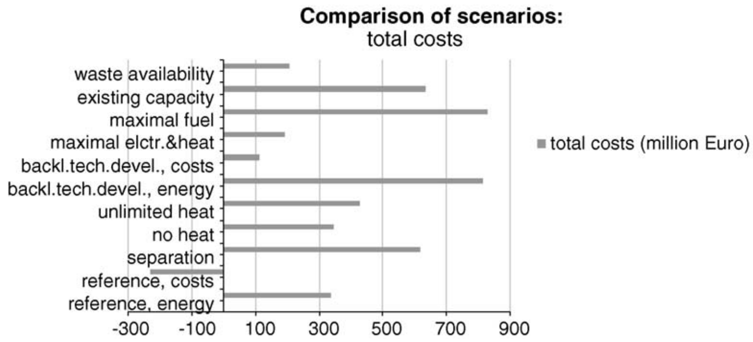

Fig. 2. Comparison of economic performance of the different scenarios.

Figs. 3–10. These figures display either the fossil primary energy savings or the costs. While the bars represent the input of wastes to a treatment option – in terms of lower heating values or market values – the dots show the respective output of a treatment option.

3.1. Scenario 1: Reference, energy

Optimisation of the reference scenario to a maximum of primary energy savings results in a rather limited number of selected waste treatment technologies; see Figs. 3 and 4. Recycled combustible streams are paper, waste tyres and waste wood, while all other combustible

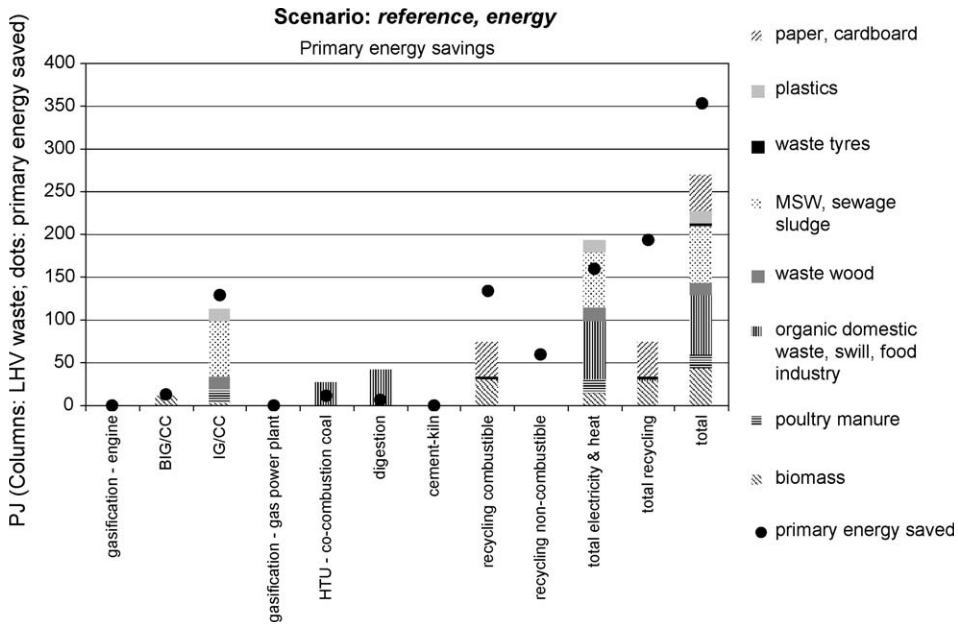

Fig. 3. Annual primary energy saving and selected technologies in the *reference, energy* scenario.

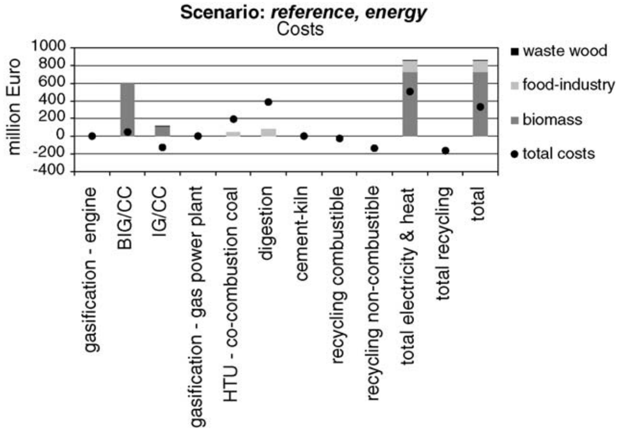

Fig. 4. Annual costs and selected technologies in the *reference, energy* scenario.

wastes are utilised for electricity production. (B)IG/CC installations with high electric efficiency treat most wastes. During optimisation, the largest possible (B)IG/CC installations are selected, because scale effects overrule the energy losses of increased transport. Remaining amounts of waste, which are too small for treatment within a (B)IG/CC, are gasified in small units with gas engines, co-fired in natural gas power plants or co-fired in cement kilns. Organic domestic waste and swill, which are both relatively wet, are only suitable for

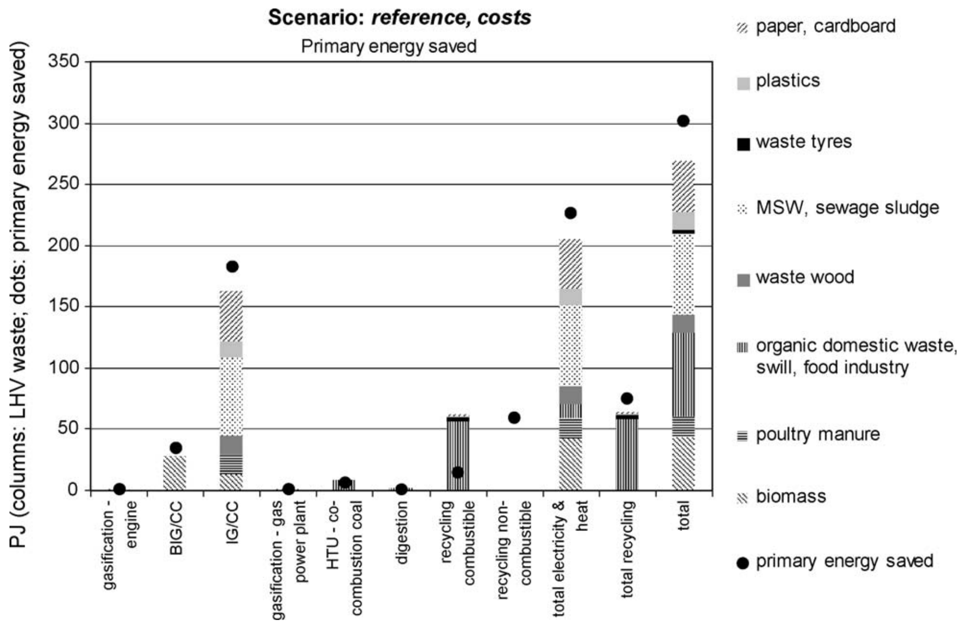

Fig. 5. Annual primary energy saving and selected technologies in the *reference, cost* scenario.

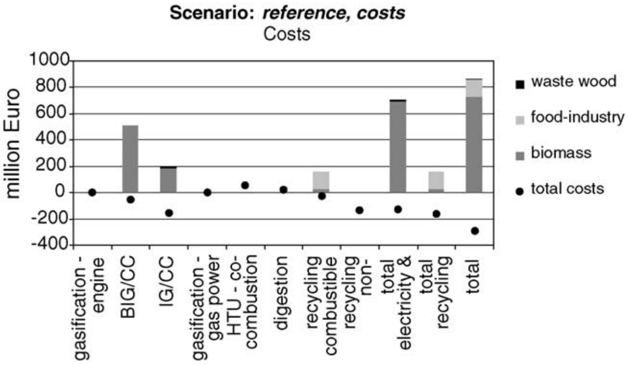

Fig. 6. Annual costs and selected technologies in the *reference, costs* scenario.

treatment by HTU or digestion. While HTU is energetically favourable, its application is limited by the co-firing capacity of HTU-oil in coal power plants. As a consequence, part of organic domestic waste and swill are digested, too.

In total, 354 PJ/year are saved in this scenario compared to a current national energy use of 3200 PJ/year. Primary energy savings of recycling (194 PJ/year) are larger than those of

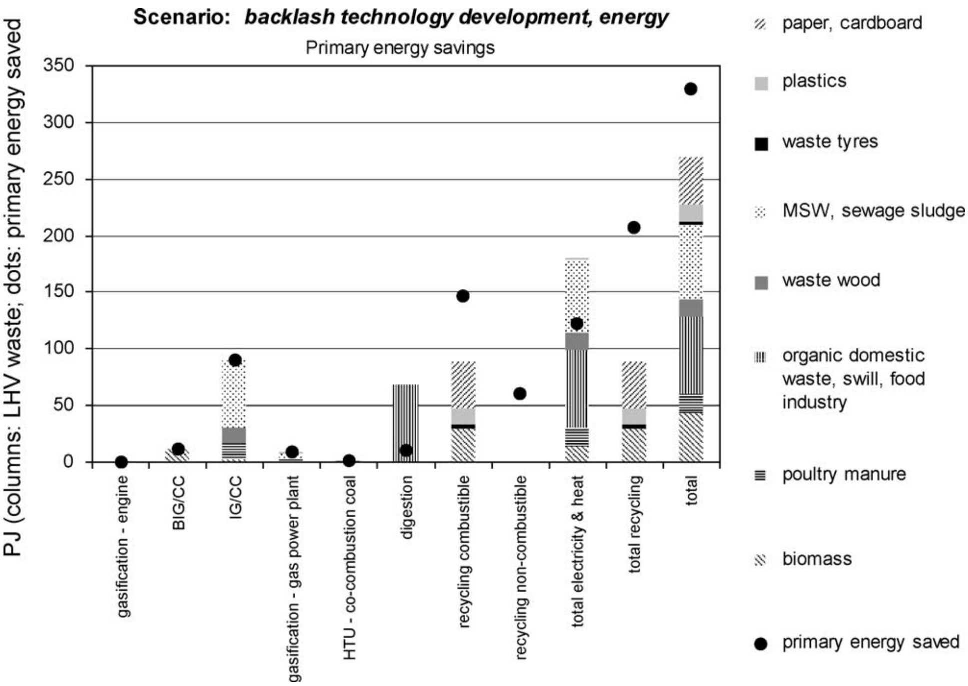

Fig. 7. Annual primary energy saving and selected technologies in the *backlash technology development, energy* scenario.

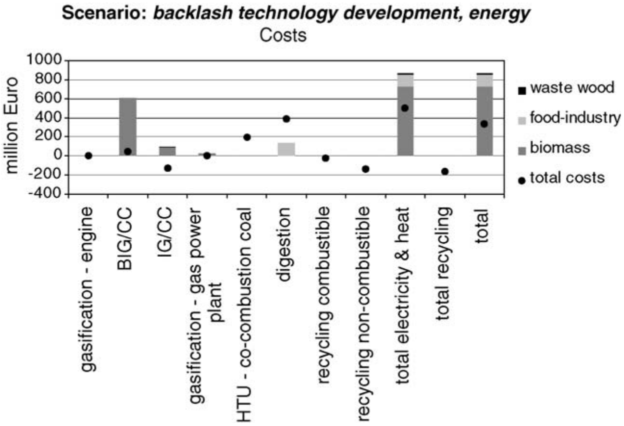

Fig. 8. Annual costs and selected technologies in the *backlash technology development, energy* scenario.

heat and power generation (160 PJ/year), even though this does not reflect the amount of wastes used for each of these purposes. The total costs per year are €335 million, i.e. average €6 Mg_{waste}^{-1} or €0.9 GJ_{saved}^{-1}. While digestion and HTU have relative high waste treatment costs, IG/CC and recycling (regarding the total of all materials recycled) are profitable.

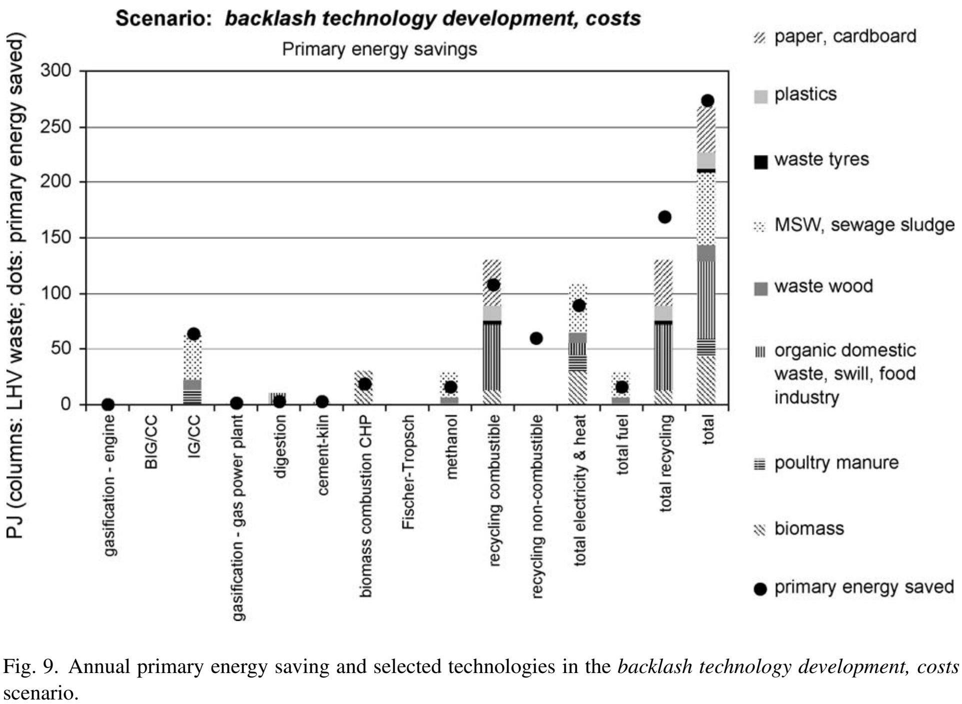

Fig. 9. Annual primary energy saving and selected technologies in the *backlash technology development, costs* scenario.

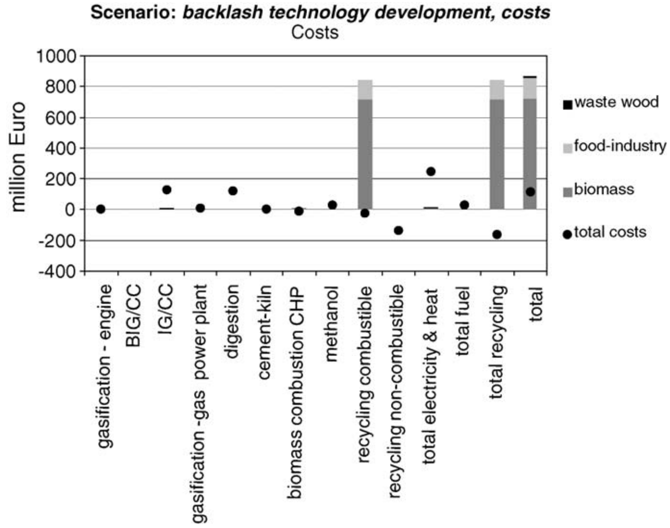

Fig. 10. Annual costs and selected technologies in the *backlash technology development, costs* scenario.

3.2. Scenario 2: Reference, costs

Optimisation of the reference scenario to a minimum of costs per unit of primary energy savings, results in a different selection of waste treatment technologies compared to an optimisation to a maximum of fossil primary energy savings (scenario 1); see Figs. 5 and 6. As in scenario 1, most biomass and waste streams are treated in (B)IG/CC installations. Remaining small amounts of waste and biomass are co-fired in cement kilns and combusted in biomass CHP-plants, respectively. HTU is also the best option to treat wet wastes in this scenario. The remains of the food processing industry, swill, waste tyres, small parts of the paper fraction and small parts of the plastic fraction are recycled. Thus, only waste tyres are recycled in scenario 1 as well as in scenario 2.

The total annual costs of €−292 million, i.e. $€-6\,\mathrm{Mg}_{\mathrm{waste}}^{-1}$ or $€-1.0\,\mathrm{GJ}_{\mathrm{saved}}^{-1}$ are negative and, thus, much lower than in scenario 1. The main reasons for this are (1) that woody residues are gasified instead of recycled and (2) that parts of the wet waste is recycled instead of treated with HTU or digestion. However, the lowered costs are at the expense of primary energy savings. Compared to scenario 1, primary energy savings decrease about 46 PJ/year and account for 302 PJ/year in total.

3.3. Scenario 3: Separation

The integrated separation of waste does not change the technologies applied compared to scenario 1. Residue derived fuel is utilised in IG/CC installations.[7] Compared to scenario 1,

[7] Separating the plastic fraction instead of accumulating it in the RDF fraction does not lead to different results. This is due to the fact that the plastic fraction is utilised in IG/CC installations, too.

total annual primary energy savings increase about 8 PJ. Even though primary energy savings of recycling increase significantly by waste separation, lower primary energy savings of heat and power production and the energy use of separation (about 2 PJ/year) off-set these gains.

Separation of waste is unfavourable with regard to costs. Total annual costs are about €615 million. The increase of costs compared to scenario 1 is mainly due to separation costs that are about €219 million/year.

3.4. Scenario 4: No heat

Although in this scenario no heat was utilised, annual primary energy savings are only 0.5 PJ lower and total annual costs only 10 million higher than in scenario 1. This is due to the fact, that also in scenario 1 only 0.01 PJ/year of heat are utilised because of costs and energy losses of heat distribution.

3.5. Scenario 5: Unlimited heat

If all heat can be used without significant transport, e.g. for industrial uses, the selection of waste treatment technology changes significantly. First, relatively 'clean' biomass is treated together with wastes in IG/CC installations instead of treated separately in BIG/CC plants. Second, waste is also co-fired in natural gas combined cycle plants. These changes in technology selection are due to the fact that costs and energy uses of transportation become relatively more important if no costs and energy uses of heat distribution are taken into account. Treating biomass and waste in the same installation leads to smaller transportation distances. However, the more biomass and waste is used, the larger are the remaining transportation distances. Therefore, co-firing in natural gas plants becomes more favourable when most of the biomass and waste is already gasified in IG/CC installations.

Total primary energy savings of this scenario are only about 3 PJ/year higher compared to scenario 1, whereas 18 PJ/year of heat are additionally utilised. As costs of co-firing in natural gas plants are higher than the costs of gasification in an IG/CC, the totals cost of €429 million/year are higher than in scenario 1.

3.6. Scenario 6: Backlash technology development, energy

This scenario regards the effects that a backlash in development of (B)IG/CC and HTU technology – which are key novel concepts – would have on waste treatment that is optimised on primary energy saving; see Figs. 7 and 8. In this scenario most waste streams are still utilised in (B)IG/CC installations, even though their electrical efficiency is about 5% lower than assumed in the reference scenario. The plastic fraction, however, is recycled in this scenario due to these lowered efficiencies. As HTU is not available in this scenario, all wet wastes are digested.

Losses in primary energy saving as a result of the backlash in technology development are relatively limited, while costs increase strongly. Annual primary energy savings are 25 PJ lower and annual costs are €369 million higher than in scenario 1. This increase in costs is mainly caused by (1) the higher investment costs of (B)IG/CC installations, (2) the lower production of electricity in the (B)IG/CC installations and (3) the higher treatment costs for wet waste streams, that have to be digested instead of treated by HTU.

3.7. Scenario 7: Backlash technology development, costs

Assuming a backlash in technology development, changes the selection of technologies considerably if waste treatment is optimised to a minimum of costs per unit of primary energy savings; see Figs. 9 and 10. In this scenario, methanol production and IG/CC are the best options for combustible waste. These technologies are close to each other with regard to costs and, therefore, the optimisation tool selects both technologies depending on respective biomass and waste transportation costs. Relatively 'clean' biomass streams are combusted in CHP installations. Remains from the food processing industry, straw, waste tyres, and large parts of the paper and plastic fractions are recycled in this scenario.

The amount of annual primary energy savings is comparatively low with 273 PJ. This is due to the fact that methanol synthesis, combustion of clean biomass and recycling of straw have much lower primary energy savings than utilisation in (B)IG/CC installations. The costs of €110 million/year are higher than in scenario 2, but are still relatively low.

3.8. Scenario 8: Maximal electricity and heat production

By definition, combustible wastes are not recycled in this scenario. As a result, wastes that are recycled in scenario 1 are utilised in (B)IG/CC installations. Consequently, annual primary energy savings are about 48 PJ lower than in scenario 1, while the primary energy savings of electricity and heat production increases strongly to about 246 PJ/year. The total costs are €143 million/year lower than in scenario 1 due to the gasification of woody residues that are recycled at higher costs in scenario 1.

3.9. Scenario 9: Maximal fuel production

In this scenario, waste streams suitable for fuel production are by definition not converted to electricity and heat. As a result, technology selection differs considerably from other scenarios. In this scenario, the same wastes as in scenario 1 and the plastic fractions are recycled. Thus, plastic recycling is more favourable than fuel production with regard to primary energy savings. HTU and digestion are applied to wet wastes, i.e. organic domestic wastes, food processing remains and swill. All other biomass and waste streams are utilised for methanol production in this scenario.

Fuel production saves 62 PJ of primary energy per year.[8] In total, only 288 PJ/year of primary energy are saved in this scenario, which is 66 PJ/year less than in scenario 1.

[8] This is less than the possible primary energy savings by electricity production from the same wastes. A main reason for this is, that efficiencies of converting crude oil into gasoline are much higher than those of converting fossil fuels to electricity. As a consequence, primary energy savings of the production of 1 GJ fuel are lower than those of the production of 1 GJ electricity.

Table 5
Biomass and waste treatment installations in scenario 1 (excluding recycling) in order of selection

Technology	Scale $MW_{th\text{-}input}$	Province	Heat (GJ)	Input (ktonnes)	Efficiency MJ_{prim}/MJ_{LHV}	Energy saved (PJ)	Costs (€/tonnes)	Costs (€/GJ_{prim})	Total costs million (€)
(B)IG/CC	1000	Groningen	0.0	2539	1.2	34.6	−43.6	−1.5	−53.4
IG/CC	1000	Friesland	0.0	2608	1.1	25.7	−17.1	−1.3	−34.1
IG/CC	1000	N.-Holland	0.0	2431	1.1	25.8	−16.8	−1.1	−28.2
IG/CC	1000	Gelderland	0.0	2595	1.1	25.8	−13.9	−0.9	−24.0
IG/CC	1000	Limburg	0.0	2621	1.1	25.8	−13.6	−0.9	−23.7
IG/CC	1000	Noord-Brabant	0.0	2591	1.1	25.8	−15.0	−1.1	−27.2
IG/CC	1000	Gelderland	0.0	2508	1.1	25.7	−12.8	−0.8	−20.5
IG/CC	1000	Z.-Holland	0.0	2437	1.1	25.8	−7.9	−0.3	−7.1
Biomass CHP	50	Zeeland	0.0	149	0.6	0.8	−4.9	−0.9	−0.7
Cement kiln	50	Limburg	0.0	177	0.8	1.2	15.2	1.9	2.2
IG/CC	100	Zeeland	0.0	280	0.9	2.0	19.3	3.6	7.2
HTU	250	N.-Holland	0.0	1640	0.8	4.8	24.7	8.1	38.7
HTU	100	Z.-Holland	0.0	655	0.7	1.9	32.5	10.6	20.0
Digestion	30	Limburg	0.0	217	0.3	0.2	38.6	32.5	7.9
Digestion	30	Drenthe	0.0	220	0.3	0.2	42.6	36.5	8.8
Digestion	15	Groningen	0.0	108	0.3	0.1	52.7	44.8	5.4
Total	8625		0.0	23778	1.1	226.5	−11.2	−0.6	−128.8

Table 6
Biomass and waste treatment installations in scenario 2 (excluding recycling) in order of selection

Technology	Scale $MW_{th\text{-}input}$	Province	Heat (GJ)	Input (ktonnes)	Efficiency MJ_{prim}/MJ_{LHV}	Energy saved (PJ)	Costs (€/tonnes)	Costs (€/GJ_{prim})	Total costs million (€)
BIG/CC	400	Drenthe	0.5	1088	1.1	12.9	−19.7	3.6	46.1
IG/CC	1000	Z.-Holland	1.0	2503	1.1	25.8	−17.1	−1.0	−24.7
IG/CC	1000	N.-Brabant	1.0	2745	1.1	25.8	−11.8	−0.7	−17.5
IG/CC	1000	Gelderland	1.0	2729	1.1	25.8	−14.6	−1.1	−27.4
IG/CC	1000	N.-Holland	1.0	2503	1.1	25.8	−18.1	−1.1	−29.2
IG/CC	1000	Drenthe	1.0	2756	1.1	25.7	−15.3	−1.1	−28.0
Co-firing nat. gas	30	Zeeland	0.6	65	1.0	0.5	52.0	7.9	4.1
Cement kiln	10	Limburg	0.0	32	0.8	0.2	29.8	3.7	0.9
HTU	300	Z.-Holland	1.6	2493	0.8	5.8	31.1	17.2	99.0
HTU	200	N.-Holland	1.1	1637	0.8	3.8	29.0	16.2	62.1
Gasif., gas engine	3	Zeeland	0.8	9	0.5	0.0	0.2	36.2	1.0
Digestion	44	Drenthe	0.0	426	0.3	0.4	43.2	58.7	21.8
Digestion	35	Groningen	0.0	338	0.3	0.3	43.2	58.2	17.2
Digestion	72	Limburg	0.0	682	0.3	0.6	43.7	57.3	34.8
Digestion	83	Overijssel	0.0	803	0.3	0.7	44.7	60.0	41.9
Digestion	259	N.-Brabant	0.0	2581	0.3	2.2	45.5	62.9	136.6
Digestion	204	Gelderland	0.0	2027	0.3	1.7	45.5	62.7	107.3
Digestion	24	Zeeland	0.0	224	0.3	0.2	45.1	58.2	11.7
Digestion	26	Friesland	0.0	259	0.3	0.2	44.0	62.9	13.7
Total	6690		9.5	25898	1.0	158.4	9.1	3.0	471.4

Moreover, total costs are with €829 million/year significantly higher than in scenario 1 as methanol synthesis is a relatively expensive option.

3.10. Scenario 10: Existing capacity

In this scenario, waste treatment installations that are currently constructed or planned still operate in 2020. However, these installations cannot utilise more than 4% of the available amount of biomass and waste. Due to this less optimal utilisation of biomass and waste, annual primary energy savings are 24 PJ lower and annual costs are €289 million higher compared to scenario 1.

3.11. Scenario 11: Waste availability

The fact that in this scenario the amount of waste is higher compared to scenario 1 does not influence the selection of technologies. Nevertheless, the primary energy savings increase to 437 PJ/year of which 225 PJ/year are saved by means of recycling. Moreover, total costs decrease to €207 million/year, because the amount of waste, which can be treated profitable, (i.e. by recycling or IG/CC) increases more than the streams that require a more expensive treatment.

3.12. Overall findings: small-scale versus large-scale

Generally, large-scale utilisation and treatment of biomass and waste (capacities of 400–1000 $MW_{th\text{-}input}$) is favoured in the scenario analyses. With the given distribution of biomass and waste, the costs per unit of primary energy saved of the technologies decrease and the primary energy saving efficiencies increase with up-scaling. This is in spite of costs and energy losses biomass and waste transport and heat distribution (Dornburg et al., 2006).

Tables 5 and 6 present the installations selected in the reference scenarios, i.e. scenarios 1 and 2. During optimisation, first large-scale (B)IG/CC installations are selected. The more the amount of available biomass and waste decreases within the procedure, the more small-scale options are selected. Also in the other scenarios, large-scale installations are selected first. An exception is the *unlimited heat demand scenario*. In that scenario, co-firing in natural gas combined cycle plants after gasification is selected with scales of 30–180 $MW_{th\text{-}input}$. Economies of scale play small role in this case, because the size of the natural gas plants is fixed and only the amount of waste for co-firing is varied. Effects of transportation then favour small installations.

4. Discussion

The costs are calculated using the market prices of biomass and waste, energy carriers and recycling materials, while no subsidies are taken into account. Therefore, the results contribute to the understanding of (1) the optimal situation without subsidies and (2) the economic break-even-points between energy carriers and recycling applications; see Dornburg et al. (2006).

Although market prices of biomass and waste are of crucial importance to the costs per unit of primary energy savings and thus, for the total costs and technology selection in the scenarios. For the year 2020, however, especially market prices for waste material are very difficult to estimate (cf. Part I of the article), while they dominate the costs of recycling options regarded. Yet, the results of this analysis provide a valuable insight in the economic break-even-points between different options.

Concerning plastic recycling, the primary energy savings (34 GJ/Mg) are based on the average composition of plastic waste. Under that assumption plastic wastes are mainly gasified in IG/CC plants, if waste treatment is optimised on primary energy savings. For some sorts of plastic waste though, recycling is favourable compared to utilisation in an IG/CC installation from an energetic point of view. The possible error in total primary energy savings, however, is small. If all plastic waste could be recycled at primary energy savings of 53 GJ/Mg, which is about the upper limit for different sorts of plastics, an additional amount of about 5 PJ/year could be saved.

The utilisation of residues from waste incineration and gasification, i.e. slag, ash, flue gas cleaning residues, might play an important role with regard to environmental impacts (and also partly costs). The utilisation of such residues has not been considered in the analysis, as the comparison of the different technologies is not influenced significantly by it. However, if all residues would be land-filled, the costs of scenario 1 would increase about €200 million/year, while primary energy savings would decrease only about 0.5 PJ/year. If all residues could be utilised, costs and primary energy savings of the scenarios do not change significantly.[9]

5. Conclusions

From the results of the scenario analysis, conclusions regarding how, to what extent and with what economic consequences, the treatment of biomass and waste can contribute to the saving of fossil primary energy on the long term (i.e. in 2020 in The Netherlands) can be drawn. Also, the impact of policy choices and technological developments can easily be assessed. Key overall conclusions from the compiled scenarios are:

1. *Choices made on the objectives of waste treatment determine its costs strongly*. If biomass and waste treatment and utilisation is optimised towards minimum costs per unit of primary energy saved, a profit of €230 million/year results (scenario 2). On the other end of the spectrum are total costs of €830 million/year, if biomass and waste utilisation aims to produce a maximum of transportation fuel (scenario 9). For comparison, in the reference scenario optimised to a maximum of primary energy savings, total costs are €340 million/year (scenario 1).[10] Clearly, variants directed to the minimisation of costs

[9] Assumptions for this estimation are a residue production of 200 kg/tonnes$_{waste}$, average current costs of land-filling of €59 tonnes^{-1} (Werkgroep Afvalregistratie, 1999), recycled residues replace sand with a GER-value of 0.1 GJ/tonnes (Heijningen et al., 1992) and a market price of zero.

[10] In the calculations no green electricity tariffs, nor fiscal subsidies or sector-specific profitability criteria are taken into account.

have distinctively lower primary energy savings than those directed to the maximisation of energy savings (compare scenarios 1, 2 and 6, 7).

2. *Proportions between recycling and the production of energy carriers vary significantly under different preconditions*. In scenario 1, 55% of primary energy savings are achieved by recycling, while in scenario 2 this percentage is only 25%. It should, nevertheless be noted that the correct allocation of combustible wastes to recycling or energy applications is difficult. This is especially true from an economic point of view, because of unstable markets for recycling materials. Transportation fuel production is less attractive than power generation by (B)IG/CC and is not selected in most scenarios. Merely, if development of (B)IG/CC technology would be slow, methanol synthesis could be the most attractive technology to treat combustible waste from a cost point of view. (Although this option also requires technology development.)
3. *Key technologies are (B)IG/CC, HTU and waste separation*. For the treatment of combustible wastes, which are not recycled, (B)IG/CC technology is identified as optimal in most scenarios. 'More traditional' biomass and waste conversion routes, i.e. biomass combustion, waste incineration and co-firing in coal power plants, do not emerge as attractive options compared to gasification. HTU with co-firing of the produced oil in a coal power plant is energetically and economically a better option than digestion to treat wet waste streams. However, the future performance and applicability of the HTU process are uncertain, because this technology is still under development.

   Recycling of waste can contribute significantly to overall primary energy savings. Separation of waste is a precondition to recycling. Separation after collection in addition to separation at the source, however, increases total primary energy savings of waste treatment in The Netherlands only slightly (8 PJ/year) and leads to large additional costs (€280 million/year).
4. *Large-scale conversion units are mostly favourable*. Considering economies of scale in transport as well as heat distribution, the overall chain performance of most treatment technologies is better at large-scales under the assumptions made. This applies to the costs per unit of primary energy savings as well as to primary energy savings. Apart from co-firing units in natural gas combined cycle plants, the optimisation tool only selects smaller installations, if the remaining amounts of biomass or waste are small. It should be noted, that with regard to spatial distribution of heat demand as well as biomass and waste, the analysis is rather rough. It is likely, that small-scale installations might be favourable under certain circumstances as for example a high heat demand at a location where 'clean' biomass is available. On the total results of this study, however, this 'crudeness' has a minor influence.
5. *Dutch political objectives to produce energy with biomass and waste are feasible*. The third energy memorandum of the Dutch Ministry of Economic Affairs aims to supply 4.4% or 120 PJ of the national energy demand in 2020 from biomass and waste. This objective is entirely directed to the production of electricity and heat, while recycling and the production of fuel are not taken into account. The analysis shows, that utilisation of available biomass residues and other wastes could easily achieve this objective due to highly efficient conversion technologies, i.e. gasification processes. Import of biomass and/or energy cropping are, therefore, in principle necessary to achieve this objective.

If electricity and heat production from biomass and waste have the highest priority, these energy carriers could save 246 PJ of primary energy per year. If waste treatment is optimised on the overall savings of primary energy, still 160 PJ of primary energy per year are saved by electricity and heat production, even though large parts of biomass and waste are allocated to recycling applications; see scenario 1. Merely, in scenarios in which transportation fuel is produced, less than 120 PJ of primary energy are saved by electricity and heat production; see scenarios 7 and 9.

5.1. Limitations and recommended further research

In general, the optimisation tool allows for complex sensitivity analyses to evaluate the impact of different options. The results of the analysis of the Dutch waste treatment structure gives insight into magnitudes and sensitivities of primary energy savings and their costs, but is limited in predicting future situations. Therefore, it would be desirable to combine this type of analysis with forecasting models to create better insight in possible policy options and their impacts. Especially, the in and outs of recycling (economic as well as energetic) and the possible dynamic of applications and prices in time deserve more attention and further study. This aspect is important to define politic priorities, because recycling has a strong influence on total primary energy savings.

Acknowledgements

The authors are grateful to the Ministry of Housing, Spatial Planning and the Environment of The Netherlands for financial support of this study.

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