

Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion

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Abstract

The aim of this consequential life cycle assessment (LCA) is to compare district heating based on waste incineration with combustion of biomass or natural gas. The study comprises two options for energy recovery (combined heat and power (CHP) or heat only), two alternatives for external, marginal electricity generation (fossil lean or intense), and two alternatives for the alternative waste management (landfill disposal or material recovery). A secondary objective was to test a combination of dynamic energy system modelling and LCA by combining the concept of complex marginal electricity production in a static, environmental systems analysis. Furthermore, we wanted to increase the methodological knowledge about how waste can be environmentally compared to other fuels in district-heat production. The results indicate that combustion of biofuel in a CHP is environmentally favourable and robust with respect to the avoided type of electricity and waste management. Waste incineration is often (but not always) the preferable choice when incineration substitutes landfill disposal of waste. It is however, never the best choice (and often the worst) when incineration substitutes recycling. A natural gas fired CHP is an alternative of interest if marginal electricity has a high fossil content. However, if the marginal electricity is mainly based on non-fossil sources, natural gas is in general worse than biofuels.

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1. Introduction

1.1. Fuels in Swedish district heating

District heating (DH) is available in approximately 200 larger and 300 smaller built-up areas in Sweden. About 75% of all Swedish blocks of flats and approximately 140,000 detached houses are currently heated by DH. This means that approximately 50% of all Swedish space heating is supplied by DH (Fjärrvärmeföreningen, 2001). In the future detached houses are supposed to be a larger share of the system than today as the DH systems in Sweden are still expanding, mostly in remote areas. Data on customers and fuels used are displayed in Fig. 1.

Biomass is the most important fuel in Swedish district heat production. In 2000, 28% of the energy used for

district-heat production was wood fuel (cf. Fig. 1). In addition, smaller quantities of tall oil pitch, waste wood, and peat were used in the same sector (Svensk Fjärrvärme, 2003). The use of biomass is rapidly increasing, it has increased by a factor of five since 1990 (Swedish National Energy Administration, 2002).

Solid waste amounts to 11% of the fuel consumption in Swedish district heat production (cf. Fig. 1). Within the next few years waste incineration is expected to double (Sahlin et al., 2004), making it the second most important fuel for Swedish district-heat production. This is largely due to the national Waste ordinance (SFS, 2001:1063) where landfill disposal of combustible waste is prohibited from 2002 and landfill disposal of organic waste is prohibited from 2005. A study made for the Swedish EPA (The Swedish Environmental Protection Agency, 2002) shows that—besides a slight increase of material recycling—the major part of the waste currently being disposed of at landfill will be directed to incineration. The

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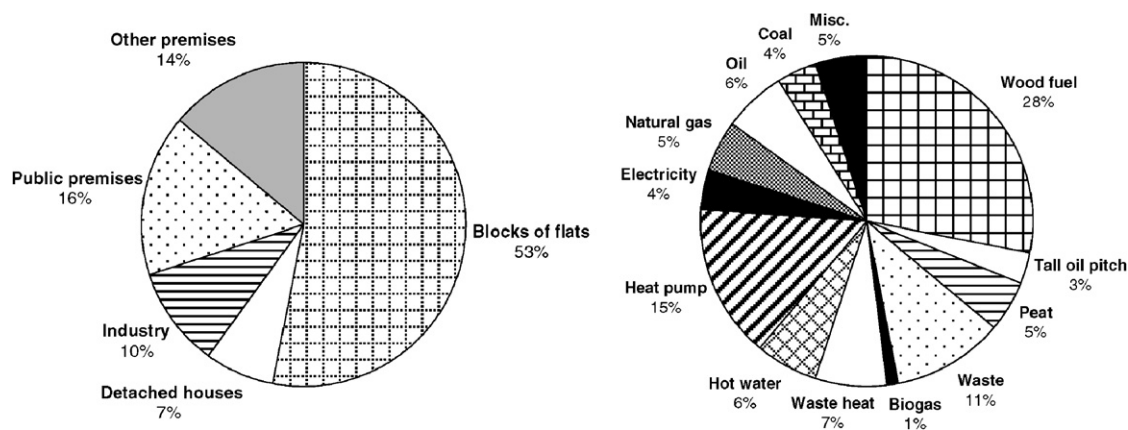


Fig. 1. Deliveries and fuel consumption in district heating in Sweden 2000 (Fjärrvärmeföreningen, 2001).

same study concludes that it is a combination of increased capacity in existing incineration plants as well as new incineration plants that will substitute landfilling. Increased waste incineration will reduce the use of existing plants using other fuels for district-heat production. It will also affect decisions to invest in new district-heat plants (for the purpose of substituting older facilities and for system expansion). The results of Sahlin et al. (2004) indicate that when an investment in waste incineration competes with another investment, the alternative to waste incineration is combustion of biomass as these two fuel types compete over the production of base-load district heat.

Only a small share of Swedish district heat is currently produced from natural gas. This is because the gas is available only at the Swedish west coast (Knutsson and Werner, 2003). A large-scale extension of the gas grid has been discussed for several years. Natural gas is currently a more expensive fuel than biomass and waste. On the other hand, natural gas allows for simultaneous production of district heat and a large share of electricity. Combined heat and power (CHP) production from natural gas might compete economically with biomass and waste over the production of base-load district heat if:

- electricity prices are sufficiently high, and
- environmental policy measures, such as systems for tradable emission permits and green electricity certificates, etc. do not undermine the competitiveness of natural gas.

The choice between biomass, solid waste and natural gas for district-heat production in Sweden can affect the electricity production in CHP plants. It can also have small effects on the electricity demand of the district-heat production. In total, the choice is still likely to have a marginal effect on the electricity system, which is integrated between the Nordic countries Denmark, Finland, Norway, and Sweden.

1.2. Life cycle assessment

Life cycle assessment (LCA) studies the environmental aspects and potential impacts throughout a product's life (i.e. from cradle to grave), from raw material acquisition through production, use and disposal (ISO, 1997). LCA is probably best known as a tool with which the life cycle impacts of physical products are assessed, but the same methodological framework also allows analysis of services such as waste management (e.g., Finnveden, 1999) and energy systems (e.g. Curran et al., 2005).

The general purpose of LCA is to provide a holistic view of the emissions and resource requirements of a product system. When applied to district-heat production, this means that the impacts of all activities involved in the extraction, refining, transport and use of the fuels are considered. These fuel chains are complex systems in themselves. The system grows even more complex as one considers the links between district-heat production and other sectors such as electricity production and waste management. The comprehensive view provided by LCA is important to avoid system sub-optimisation.

In LCA, the function provided by the analysed system is uniquely defined in terms of the functional unit. The function provided by the systems compared in this study is to produce heat for district-heating systems, and it is reasonable to define the functional unit as the production of a certain amount of district heat. Different options for district-heat production may provide different additional functions, such as generation of electricity or waste management. A fair comparison of different options requires this to be accounted for in the analysis. The ISO standards recommend that the environmental benefits of recovered resources should be accounted for by broadening the system boundaries to include the avoided burdens of conventional production (ISO, 1998; Ekvall and Finnveden, 2001).

A distinction is sometimes made between attributional and consequential LCA (Curran et al., 2005; Ekvall and Weidema, 2004; Tillman, 1999). Attributional

methodology for life cycle inventory (LCI) analysis aims at describing the environmentally relevant physical flows to and from a life cycle and its subsystems. It ideally includes average data on the unit processes. Consequential LCI methodology, in contrast, aims at describing how the environmentally relevant physical flows to and from the technosphere will change in response to possible changes in the life cycle. A consequential LCI model includes unit processes that are significantly affected whether they are inside or outside the life cycle. It ideally includes marginal data on bulk production processes in the background system (see Section 2.3.2). A consequential LCI model can also include economic partial equilibrium models (Ekvall and Weidema, 2004) and other tools that are designed to quantify specific types of causal relationships (Ekvall et al., 2004).

Waste incineration reduces the use of other waste management options. An earlier LCA aimed at comparing district-heat production from waste and other fuels in Sweden did not take this consequence of waste incineration into account (Uppenberg et al., 1999). Several other LCAs have been carried through to compare different waste management options in Sweden (e.g., Björklund and Finnveden, 2006; Eriksson et al., 2005; Finnveden et al., 2005; Moberg et al., 2005). These studies included different options for waste management as well as district-heat production; however, since the focus was on the comparison between methods for waste management, the results do not readily allow for an environmental

comparison between different options for district-heat production.

1.3. Objective

The primary aim of this study was to contribute to policy-making in the energy sector through a comparison of the environmental consequences of district-heat production from waste and competing fuels in Sweden. The study is a consequential LCA in the sense that data used reflect marginal electricity production. The study includes the environmental impacts avoided by the displaced electricity production when power is produced combined with the heat production. The study also includes other affected processes outside the life cycle of waste incineration (see Fig. 2):

- alternative waste management options (recycling and landfill),
- the material production displaced through recycling, and
- the energy production displaced through landfill.

A secondary objective was to test a combination of dynamic energy system modelling and LCA for a decision-making purpose. In this way, the study contributes to the development of methodology for consequential environmental systems analysis. Specifically, we wanted to increase the methodological knowledge about

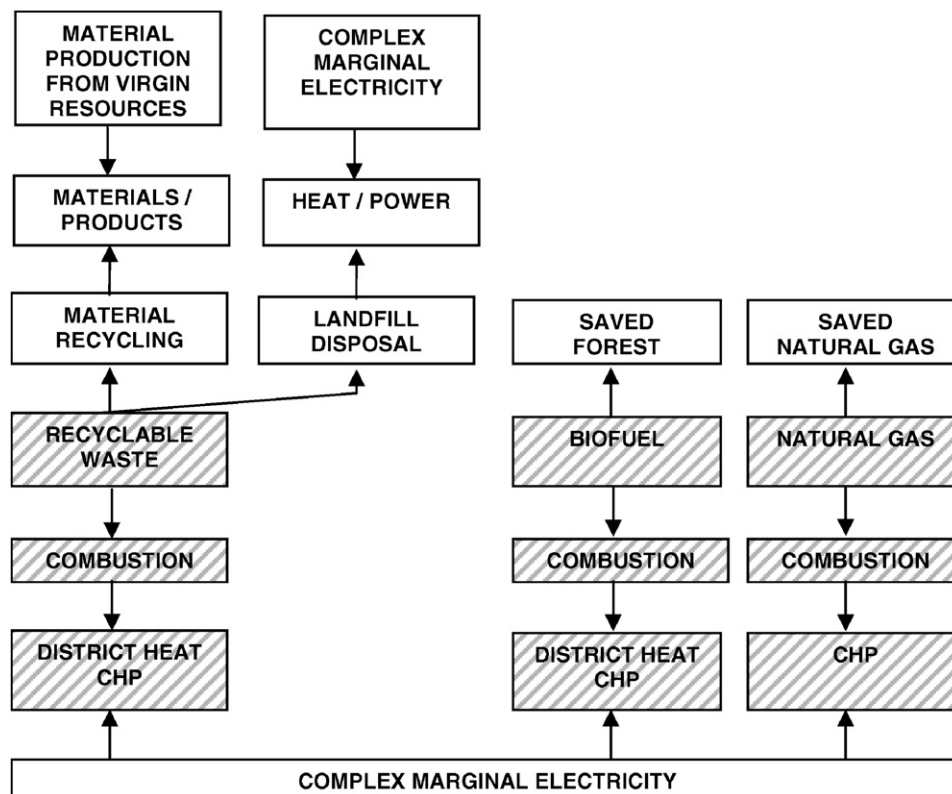


Fig. 2. The conceptual model of the system investigated. Boxes with grey stripe background are core system, and plain boxes are background system.

- how waste can be environmentally compared to other possible fuels in district-heat production,
- how the concept of complex marginal electricity production (Mattsson et al., 2006) can be utilised in a static, environmental systems analysis, and
- if the environmental ranking of fuel-based production of base-load district heat is robust with respect to different weighting methods.

2. Scope definition

The case study is based on Swedish conditions but the issue is not restricted to Sweden only since DH systems can be found in many countries in northern Europe, and the problem of fuel choice when expanding the systems or substituting older facilities is general. However, in this study the marginal electricity of the Nordic countries is used. The actual results may therefore be different for other countries.

2.1. Functional unit and options compared

The functional unit in this LCA is 42 PJ of district heat, corresponding to the amount of heat released from incineration of all waste included in the study, the results are however presented per MJ district heat. Five technologies for district-heat production are compared with different fuel and/or energy recovery:

1. waste incineration with CHP production,
2. waste incineration with district-heat production only,
3. biomass combustion with CHP production,
4. biomass combustion with district-heat production only, and
5. natural gas combustion with CHP production.

Separate district heat production from natural gas does not appear to be a realistic option for economic as well as environmental reasons.

2.2. System boundaries and limitations

Besides the core system with incineration, biomass combustion and natural gas fired CHP the background system also has to be included. The background system includes a compensatory supply system for the electricity generated, in this case modelled as avoided emissions, and other waste management alternatives, in this case landfill disposal abroad or material recycling (as landfill disposal of household waste is prohibited in Sweden). The investigated system is depicted in Fig. 2.

When biomass and natural gas are not used for producing the 42 PJ of district heat, they are assumed to remain in the forest and ground, respectively. This is a simplification of the reality: part of the biomass that is not utilised for Swedish district-heat production is likely to be

used in other parts of the international energy system, and natural gas that is not extracted within the next few decades is likely to be extracted for other purposes eventually. The motive for the simplification is that we have not been able to identify the alternative use of these resources. Expanding the system, based on speculation, to include net environmental burdens of an unknown alternative use of biomass and natural gas would not contribute to the knowledge generated in our study. However, the simplification is a significant limitation in the study (see Section 4.1).

A change in the production and use of electricity in Swedish district-heating systems will affect the Nordic electricity market. It will affect the utilisation of existing power plants, where coal condensing is the short-term marginal technology. It will also affect investments in new power plants based on technologies such as natural gas CHP and wind power (Mattsson et al., 2006). The compensatory system for electricity supply includes the mix of technologies that can be assumed to be affected by the Swedish district-heat production (see Section 2.3.2).

The wastes included in this study are recyclable wastes that are possible to combust, recycle or dispose of at a landfill. Landfill disposal of combustible waste is prohibited in Sweden. This means that the competing treatment method for the waste in Sweden is recycling. There are EU policies suggesting that waste should be treated near its source and there are some restrictions regarding waste trade. However, there is some export and import of waste (Olofsson et al., 2005) suggesting that the marginal waste management may be outside Sweden. In this study, we have modelled two scenarios for the competing waste treatment: recycling in Sweden or landfilling in another EU country. The avoided landfilling is supposed to have a standard similar to Sweden, as the landfill directive is common for all member states.

2.3. Inventory data and assumptions

This study benefits from using an existing model of waste management in Sweden (Björklund et al., 2003) (Fig. 3). The model was implemented in the LCA software tool SimaPro 5 (Goedkoop and Oele, 2001).

2.3.1. Waste flows

Waste fractions included in this study are basically those that can be incinerated, disposed of at a landfill or recycled, given that data for such a recycling process is provided, see Table 1. The amounts and composition of waste are estimates of Swedish waste flows in 2008. Estimates were reached by making inventories of current (1998–2000) waste amounts, which were then extrapolated to 2008 based on different growth rates for different waste categories.

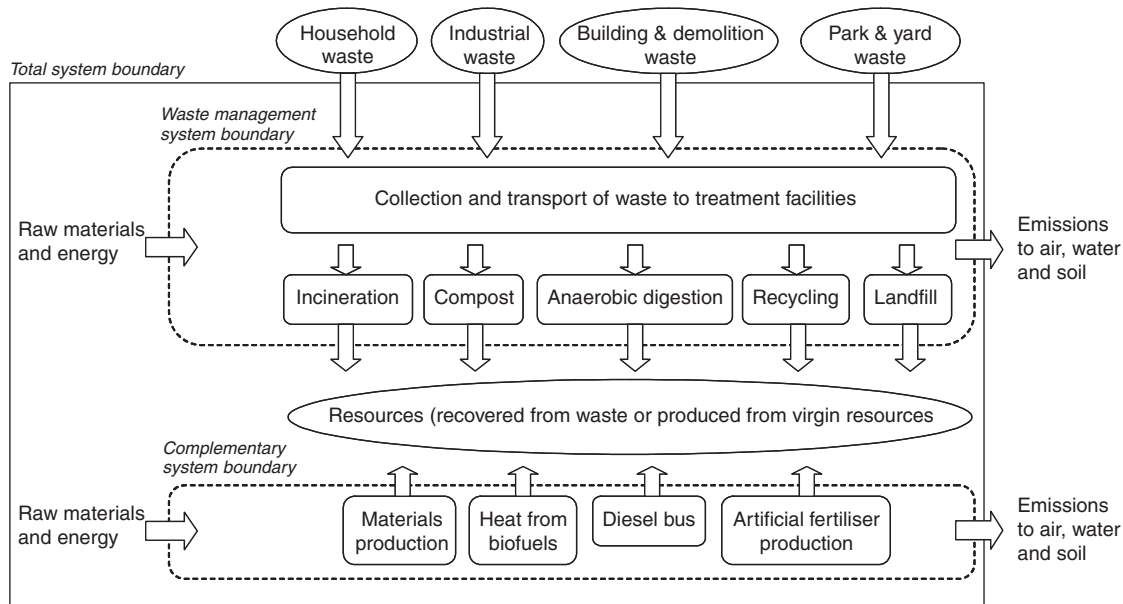


Fig. 3. Illustration of the LCA model developed by Björklund et al. (2003).

Table 1
Waste fractions included in the study (Björklund et al., 2003)

Waste fraction	Amount (tonnes)
Build and demolition waste	
Mixed paper	60,153
Household waste	
Compost	752,942
Mixed plastic	158,678
Newspaper	678,394
Office paper	351,099
Corrugated cardboard	292,781
Cardboard	235,653
Polypropylene (PP)	17,495
Polystyrene(PS)	13,996
Polyethylene (PE)	129,799
Polyvinylchloride (PVC)	5332
Polyethylene (PET)	9997
Industrial waste	
Mixed paper	677,173
Mixed plastic	199,787
Park & yard waste	241,603

2.3.2. Submodels and input data

The waste incineration model allows incineration of all combustible materials appearing in the case study. Emission factors were derived using the ORWARE model (Eriksson et al., 2002). Recovered energy was assumed to replace heat from biofuels at a 1:1 replacement ratio. Ashes from biofuel combustion are assumed to be spread in the forest. Similar to the landfill described below, leaching of metals from these ashes was modelled for a short time frame in the base case, but also a hypothetical infinite time frame.

Data for CHP incineration is based on the conditions for the current models for DH only in Björklund et al. (2003). The energy recovery has been changed, where the degree of efficiency is still 90%, but the energy is released both as heat and electricity. The partition between electricity and heat has been collected from a modern large-scale incineration plant in Sweden (Umeå Energi AB, 2004). This plant generates 65 MW “useful energy” whereof 55 MW as district heat and 10 MW as electricity. Data on annual energy production were not available. Therefore, the same distribution of heat and electricity as the figures in MW has been assumed. Emissions and resource consumption were allocated per unit energy recovered.

One of the competing fuels to waste is biofuel. To model biofuel DH, we used an existing dataset that represent “heat from residues from timberfelling” (Finnveden et al., 2000). For CHP we used the same data, but added a power-to-heat ratio based on data from a modern biomass fired CHP in the city of Eskilstuna (Eskilstuna Energi AB, 2004) in Sweden and calculated to 0.45 where heat from flue gas condensation has been included. Another study (Knutsson and Werner, 2003) sets the corresponding figure to 0.50. The power-to-heat ratio for natural gas CHP has been set to 1.10 according to (Knutsson and Werner, 2003). Emission data used are from Uppenberg et al. (1999).

Marginal effects are the consequences of infinitesimal or small changes in the volume produced of a good. Many actions can be expected to have marginal effects on the production of bulk materials (e.g., steel, aluminium, polyethylene) and energy carriers (e.g., electricity, fuel oil, petrol). Any electricity use in the investigated systems will affect the electricity production system at the margin. Similarly, any electricity delivered from CHP plants in the

Swedish district-heating systems will affect the Nordic electricity system at the margin.

Marginal effects should, ideally, be modelled using marginal data that, by definition, reflect the environmental burdens of the technology affected by a marginal change (Weidema, 1993). If we account for the fact that a change in electricity use can affect investments in new power plants and the closing of old power plants, accurate identification of the marginal electricity production becomes difficult. The marginal electricity can be dominated by extended use of old coal-power plants, by the postponed closing of Swedish and German nuclear reactors, or by the construction of new CHP plants for natural gas, etc. Such effects are, in the context of LCA denoted long-term marginal effects (Weidema et al., 1999).

The marginal technologies are often identified using static models of the electricity system, but they can also be analysed using dynamic optimising models (Mattsson et al., 2006). The latter approach gives a more complete description of the consequences of using or delivering electricity, because it takes into account effects on the utilisation of existing production facilities as well as effects on investments in new production facilities. Dynamic optimising modelling is one type of technique that can be used to generate external scenarios (Börjeson et al., 2006).

Mattsson et al. (2006) investigated how a dynamic optimising model of the production of electricity and district heat in the Nordic countries reacts to a change in the Nordic electricity demand or the Swedish nuclear power production. We use the model reactions to small changes in the electricity demand to identify the marginal technologies for electricity production. The model, Nordic Electricity Supply optimisation (NELSON), is based on linear programming and follows in the tradition of bottom-up energy system models such as MARKAL or EFOM (Fishbone and Abilock, 1981; Finon, 1979). It calculates how a given electricity and heat demand can be supplied at least cost during a 50-year period. The results from Mattsson et al. demonstrate that the marginal electricity production in the Nordic countries is complex in the sense that it involves several different technologies. The mix of technologies is uncertain because it depends heavily on assumptions regarding uncertain boundary conditions, future fuel prices, etc. From the results of Mattsson et al. we use two extremes (see Table 2), based on different scenarios for fuel prices and boundary conditions:

- High environmental impact: the price on natural gas at the Nordic border increases linearly to 115 SEK/MWh in 2050. As a result, the marginal electricity production includes a large share of coal.
- Low environmental impact: the CO₂ emissions from the Nordic electricity and district-heat production decreases linearly to a 50% reduction in 2050, because of a hypothetical cap on the CO₂ emissions. As a result of this cap, any additional electricity demand must be met

Table 2

Complex marginal electricity production in two different scenarios for the future Nordic energy system (Mattsson et al., 2006)

%	High environmental impact	Low environmental impact
Wind	11.32	21.79
Nuclear	00.00	23.09
Biomass CHP	00.53	35.72
Coal condense	59.99	00.77
Oil condense	03.03	-01.41
Natural gas CHP	25.33	19.95
Hydro power	-00.21	00.10

Table 3

References for emissions of complex marginal electricity

Power source	g CO ₂ /MJ el	Reference
Wind	1.8	Uppenberg et al. (2001)
Nuclear	3.1	Uppenberg et al. (1999)
Biomass CHP	0.87	Uppenberg et al. (1999)
Coal condense	212	Björklund et al. (2003)
Oil condense	81.9	Uppenberg et al. 1999
Natural gas CHP	60.3	Uppenberg et al. (1999)
Hydro power	1.4	Brännström-Norberg et al. (1996)

without an increase in CO₂ emissions from the combined Nordic electricity and district-heat systems.

These scenarios were developed independently of our study, and none of them exactly fit the purpose of our study. For example, a Nordic CO₂ cap on the combined Nordic electricity and district-heat systems no longer appears to be a realistic scenario. It would also mean that the choice between natural gas and biofuel to replace Swedish waste incineration would not affect the total CO₂ emissions of this energy system. We still choose to use these electricity scenarios because they illustrate the large uncertainty in the identification of the marginal electricity production (see above).

The emissions for the fuels used were not supplied by the NELSON model. Instead, database data according to Table 3 have been applied.

The submodels for the waste management system are described in detail in Björklund et al. (2003) and Björklund and Finnveden (2006). Emissions and fuel consumption for waste collection were modelled as depending on the weight of collected waste and average distance travelled, with different average distances applied for the different treatment options. Emission factors of the anaerobic digestion plant and composting were derived from the ORWARE model. Digester and composting residues were assumed to replace nitrogen and phosphorus in artificial fertiliser at a 1:1 replacement ratio. Nutrient leaching from digester sludge and compost were assumed to be equal to those from artificial fertiliser. Biogas was assumed to be

used as bus fuel, replacing diesel fuel at a 1:1 replacement ratio.

Modelled material recycling processes include aluminium, steel, cardboard, corrugated cardboard, glass, newsprint, office paper, plastics (PE; PET, PP; PS, PVC), plaster board, concrete and asphalt. While many recycled materials were assumed to replace an equivalent amount of virgin material, some were modelled as replacing other types of material, and in some cases the replacement ratio recycled:virgin material was less than 1:1 (Björklund et al., 2003). Biomass that is saved through paper and cardboard recycling is assumed to remain in the forest. Recycled concrete and asphalt are assumed to replace gravel and virgin asphalt, respectively. However, because of lack of data, no burdens were modelled for these fractions. In practice, this corresponds to the assumption that the recycling and use of recycled concrete and asphalt cause the same environmental burdens as the production and use of virgin materials.

The landfill model allows landfill disposal of all non-combustible fractions appearing in the case study. Emission factors were derived using the ORWARE model. Two time frames were modelled for landfill emissions. In the base case, called the surveyable time period, a short time frame of about 100 years was applied. After this period a large fraction of landfilled material still remains in the landfill. A long time frame was also modelled, called the remaining time period. This corresponds to a hypothetical infinite period, which allows all landfilled material to be spread into the environment (Finnveden et al., 1995).

2.4. Impact assessment methods

The characterisation methods used are CML 2000 baseline characterisation method (Guinée, 2002) except for natural resources where the thermodynamic approach was used (Finnveden and Östlund, 1997). Three LCA weighting methods were used: Ecotax 02, Eco-indicator 99, and EPS 2000. The idea behind Ecotax 02 is that we can use taxes and fees as expressions of the value society places on damages relating to the environment. The applied values for Sweden are described in detail in Finnveden et al. (2006). The method links a tax or a fee to a relevant impact category. Weighting factors are in some cases expressed as minimum and maximum values, to indicate uncertainties. Emissions from landfills may prevail for very long time periods. In order to separate short-term from long-term emissions and also to include both maximum and minimum cost estimates four versions of the Ecotax method have been developed (see Table 4).

In order to check the robustness of the weighting method applied, two commonly used LCA weighting methods were also used. The Eco-indicator method is based on an expert panel (Goedkoop and Spriensma, 2000). The EPS 2000 (Environmental Priority Strategies) evaluates impacts on the environment via its impact on several safeguards subjects; human health, resources, ecosystem production

Table 4
Weighting methods

Name	Remark	Reference
EcoTax02max(RT) ^a	Monetary based on environmental taxes and fees	Eldh (2003)
EcoTax02min(RT) ^b	Ibid.	Ibid.
EcoTax02max(RT = 0 ^c) ^a	Ibid.	Ibid.
EcoTax02min(RT = 0 ^c) ^b	Ibid.	Ibid.
Eco-indicator 99	Damage oriented. Default hierarchist perspective used in this study	Goedkoop and Spriensma (2000)
EPS 2000	Based on willingness-to-pay to restore impacts on safeguards projects.	Steen (1999)

^amax, maximum cost estimations; RT, Long-term emissions from landfill disposal are included.

^bmin, minimum cost estimations.

^cRT = 0, long-term emissions from landfill disposal are excluded.

capacity, bio-diversity and aesthetic values (Steen, 1999). The default weighting method is based on willingness-to-pay surveys to restore impacts on the safeguards subjects (ibid). The CML base line method, as well as the Eco-indicator and EPS-methods were used as implemented in the Simapro software.

2.5. Scenarios

As noted above we are looking at two different alternative waste management methods: recycling and landfilling. We are also looking at two different scenarios for the marginal electricity production: the High impact and the Low impact. When these are combined, the result is four external scenarios. Also noted above we study 5 different alternatives in these four external scenarios, resulting in 14 different combinations as described in Table 5.

3. Results

Previous studies have indicated that the most significant impact categories for waste management may be use of natural resources, global warming and toxic emissions (Finnveden et al., 2005). Here we focus on the use of energy, global warming potential and the total weighted results.

When comparing the five alternatives, this is suggested to be done for each scenario. This means that the following four sets of combinations can be read at a time:

Combinations 1–5: high environmental impact electricity and material recycling.

Table 5
Combinations simulated

Nr	Fuel	Energy recovery	Electricity scenario	Avoided waste treatment
1	Waste	CHP ^a	High environmental impact	Material recycling
2	Waste	DH ^b	High environmental impact	Material recycling
3	Biofuel	CHP	High environmental impact	—
4	Biofuel	DH	High environmental impact	—
5	Natural gas	CHP	High environmental impact	—
6	Waste	CHP	High environmental impact	Landfilling
7	Waste	DH	High environmental impact	Landfilling
8	Waste	CHP	Low environmental impact	Material recycling
9	Waste	DH	Low environmental impact	Material recycling
10	Biofuel	CHP	Low environmental impact	—
11	Biofuel	DH	Low environmental impact	—
12	Natural gas	CHP	Low environmental impact	—
13	Waste	CHP	Low environmental impact	Landfilling
14	Waste	DH	Low environmental impact	Landfilling

^aCHP = combined heat and power generation.

^bDH = district-heating generation.

Combinations 3–7: high environmental impact electricity and landfilling.

Combinations 8–12: low environmental impact electricity and material recycling.

Combination 10–14: low environmental impact electricity and landfilling.

3.1. Primary energy turnover

Incineration where material recycling is avoided (scenarios 1–2, 8–9) has net energy use of non-renewable energy, regardless of the type of replaced electricity. This comes from that oil is used for production of virgin plastic. Incineration where landfill disposal is avoided (scenarios 6–7, 13–14) saves renewable energy and uses non-renewable energy, regardless of the type of replaced electricity. Biomass combustion only saves energy as a CHP (scenarios 3, 10). A natural gas fired CHP (scenario 12) saves renewable energy, but does also use non-renewable energy (Fig. 4).

Given a high-impact electricity mix and landfilling as alternative waste management (scenarios 3–7) the largest energy savings is found for waste incineration in a CHP (scenario 6). On second place comes a DH plant

(scenario 7). Given a high-impact electricity mix and material recycling as alternative waste management, CHP fired with biomass gives the largest savings of non-renewable energy (scenario 3).

3.2. Global warming potential

Waste incineration with avoided landfilling (scenarios 6–7, 13–14) give the largest savings in GWP, regardless of type of avoided electricity mix. Out of these, incineration in a CHP gives the largest savings, especially for a high-impact electricity mix (scenario 6). Waste incineration with avoided recycling (1–2, 8–9) gives net contribution to GWP, regardless of the marginal electricity source (Fig. 5).

Biomass combustion (3–4, 10–11) is best performed as CHP, especially in combination with a high gas price as fossil intense power is then replaced. Natural gas fired CHP gives a negative GWP contribution with a high-impact electricity mix (5) but a high positive with the other marginal alternative (12).

3.3. Weighted result

Waste incineration with avoided landfilling (6–7, 13–14) has a much better result than if material recycling is avoided (1–2, 8–9). Combustion of natural gas (5, 12) that has a high electricity generation can be preferred if the electricity avoided has a high degree of coal combustion (5) (Fig. 6).

3.4. Sensitivity analysis

The sensitivity analysis includes other weighting methods, as explained in Chapter 2.4 impact assessment methods.

3.4.1. EcoTax02Min

The conclusion drawn from Fig. 5a and b holds true in Fig. 7a and b. It just becomes more obvious and clear as all bars seems to have been extended (in fact they have shrunken, looking at scale on the Y-axis). The results are dominated by toxicity impacts. For scenarios 6–7 and 13–14 GWP also plays a role as a decreased landfill disposal also decreases methane emissions from landfills.

3.4.2. EcoTax02Max(RT = 0)

Applying the EcoTax02Max(RT = 0) method, the lowest environmental impact is found for biofuel CHP (3, 10) (Fig. 8).

3.4.3. EcoTax02Min(RT = 0)

Given a high-impact electricity mix a natural gas fired CHP (scenario 5) is most favourable option in this case, biofuel CHP (3) comes second. Waste incineration with avoided landfilling (6, 7) also gives a negative impact (Fig. 9).

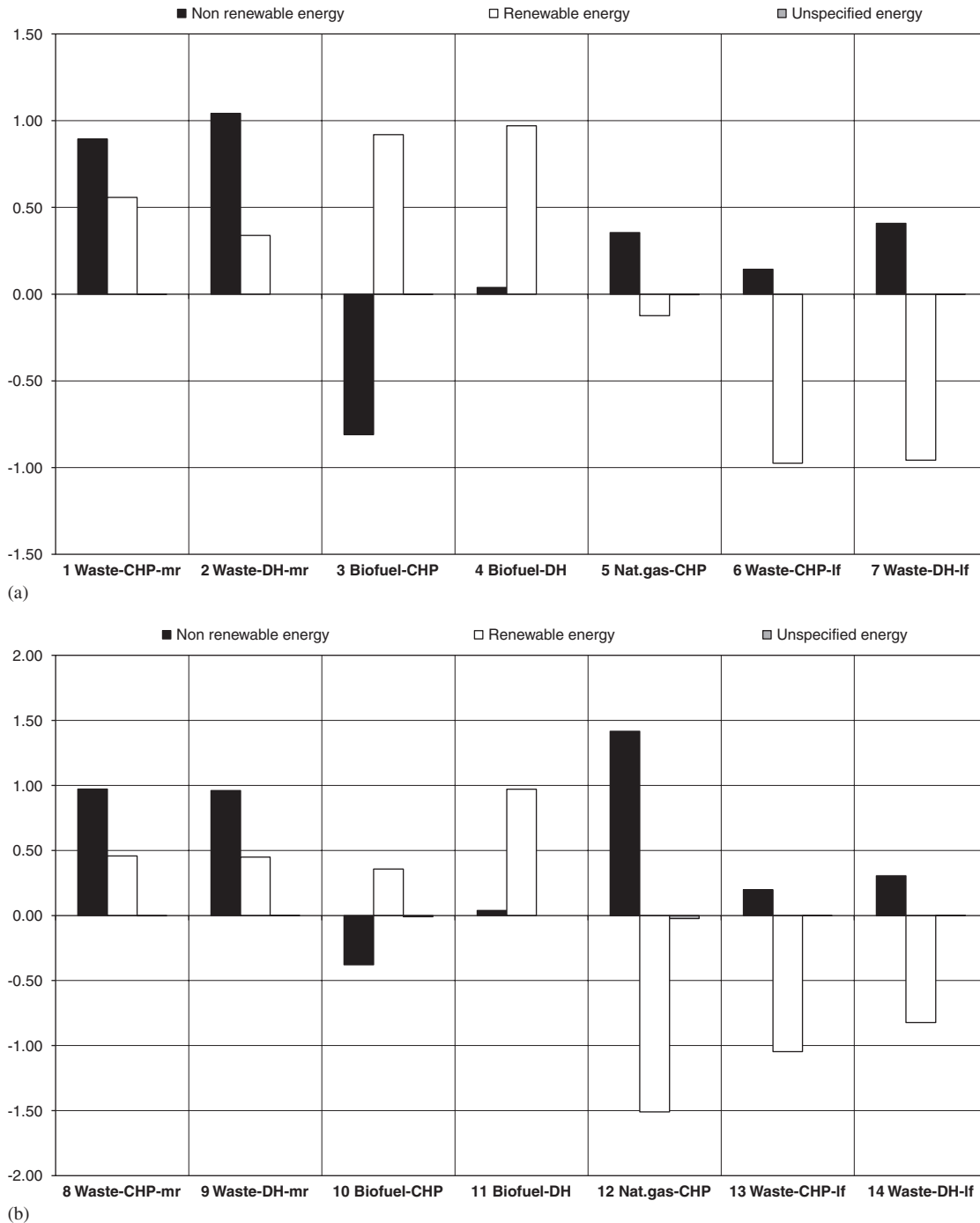


Fig. 4. (a) Primary energy turnover for scenarios 1–7 (high environmental impact). Units in MJ/MJ heat. (b) Primary energy turnover for scenarios 8–14 (low environmental impact). Units in MJ/MJ heat.

3.4.4. Eco-indicator 99

Also for this method waste incineration (scenarios 6–7, 13–14) seems to be the best option when landfilling is the alternative waste management. The scenarios with avoided material recycling (1–2, 8–9) are dominated by human health carcinogenic and secondly resource consumption of fossil fuels (Fig. 10).

Biomass combustion (3–4, 10–11) is the best option, especially CHP with a high-impact electricity mix (3), when recycling is the alternative waste management. Natural gas fired CHP (scenarios 5 and 12) has an overall negative environmental impact with this method. The result is dominated by resource consumption of fossil fuels. Environmental quality ecotoxicity has an almost equal

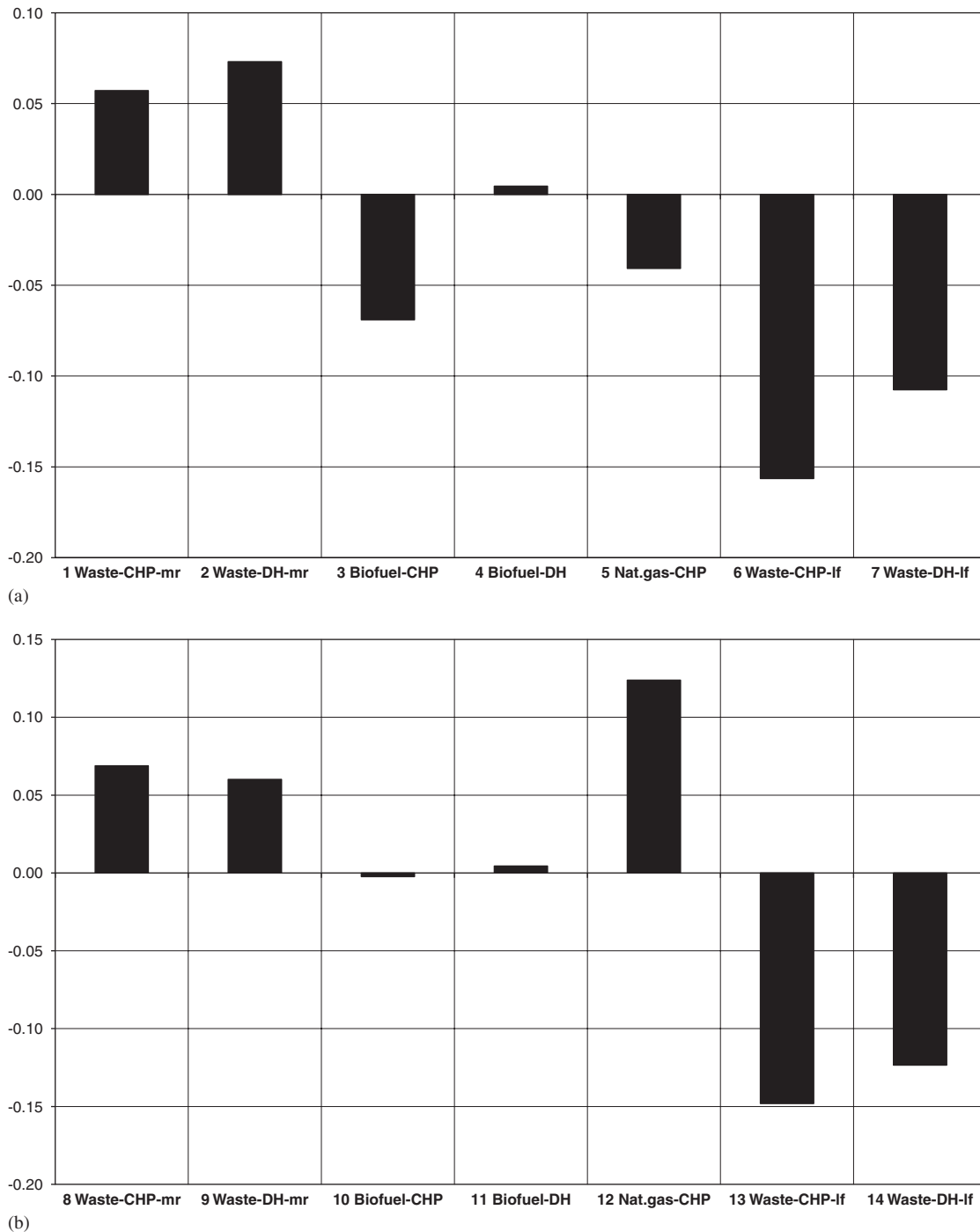


Fig. 5. (a) Global warming potential (100 years) for scenarios 1–7 (High environmental impact). Units in kg CO₂-eq./MJ heat. (b) Global warming potential (100 years) for scenarios 8–14 (low environmental impact). Units in kg CO₂-eq./MJ heat.

contribution (4E7) for all scenarios. It is positive for biomass combustion and negative for the other scenarios.

3.4.5. EPS 2000

The only scenario with a negative EPS result is biofuel combustion in a CHP, which can be seen in

both 11a and b. In scenarios 3 and 10 abiotic stock resource plays a dominant role in the negative impact, for scenario 3 also human health. The other scenarios cause an environmental impact, especially natural gas combustion. Abiotic stock resource is dominant for the scenarios with natural gas combustion (Fig. 11).

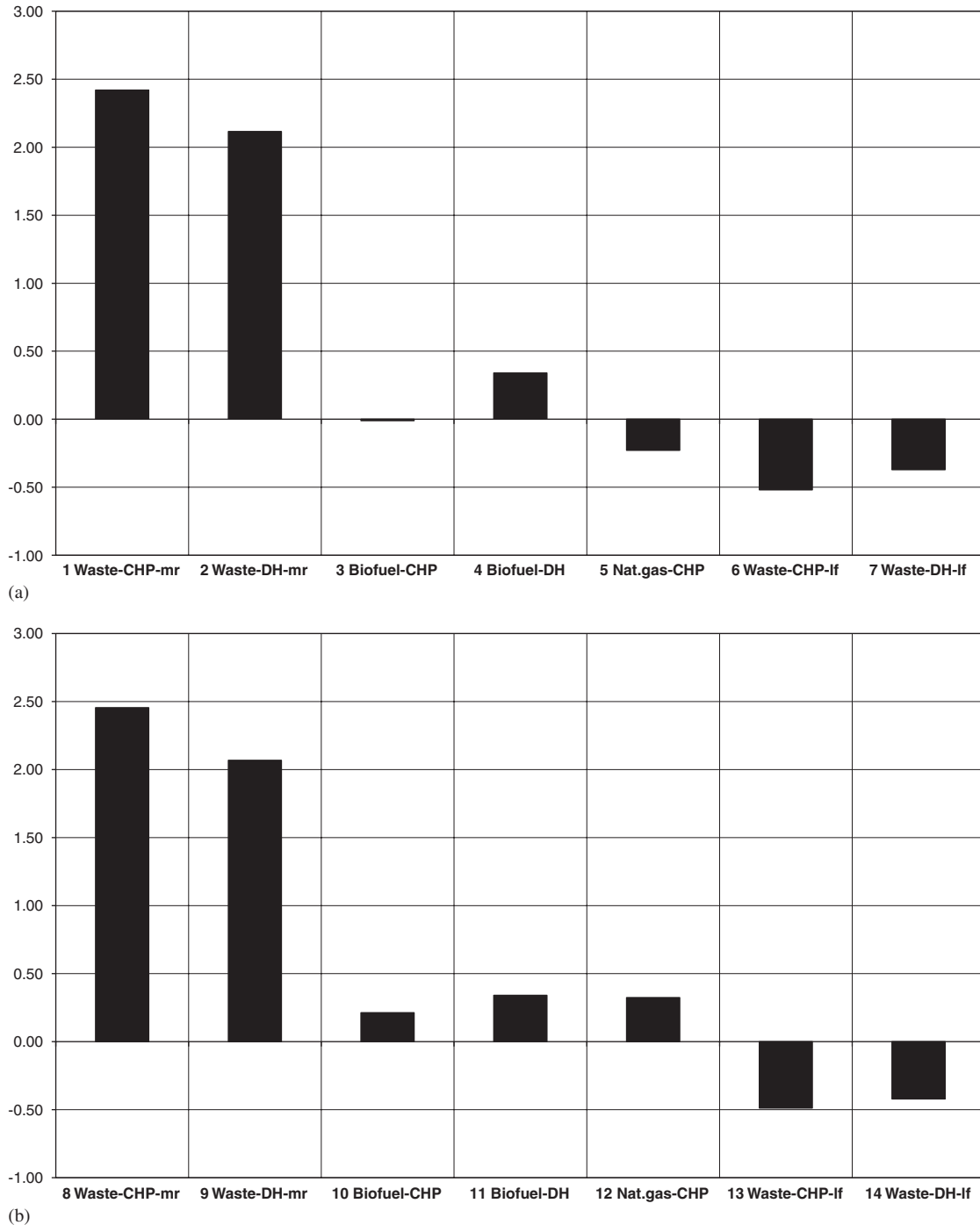


Fig. 6. (a) Weighted result for scenarios 1–7 (high environmental impact). Units in SEK/MJ heat. (b) Weighted result for the scenarios 8–14 (low environmental impact). Units in SEK/MJ heat.

4. Discussion and conclusions

4.1. Policy relevant conclusions

A number of policy-relevant conclusions can be drawn from the results presented above.

CHP has environmental advantages compared to only DH. The advantages become stronger when the marginal

electricity production is associated with high emissions. Policies promoting CHP instead of only heat production are therefore environmentally good.

The study is based on the assumption that the marginal electricity production is a Nordic marginal. This assumption can be defended by the fact that the electricity trade is most efficient within the Nordic area, where a common market for electricity exists. However, the Swedish

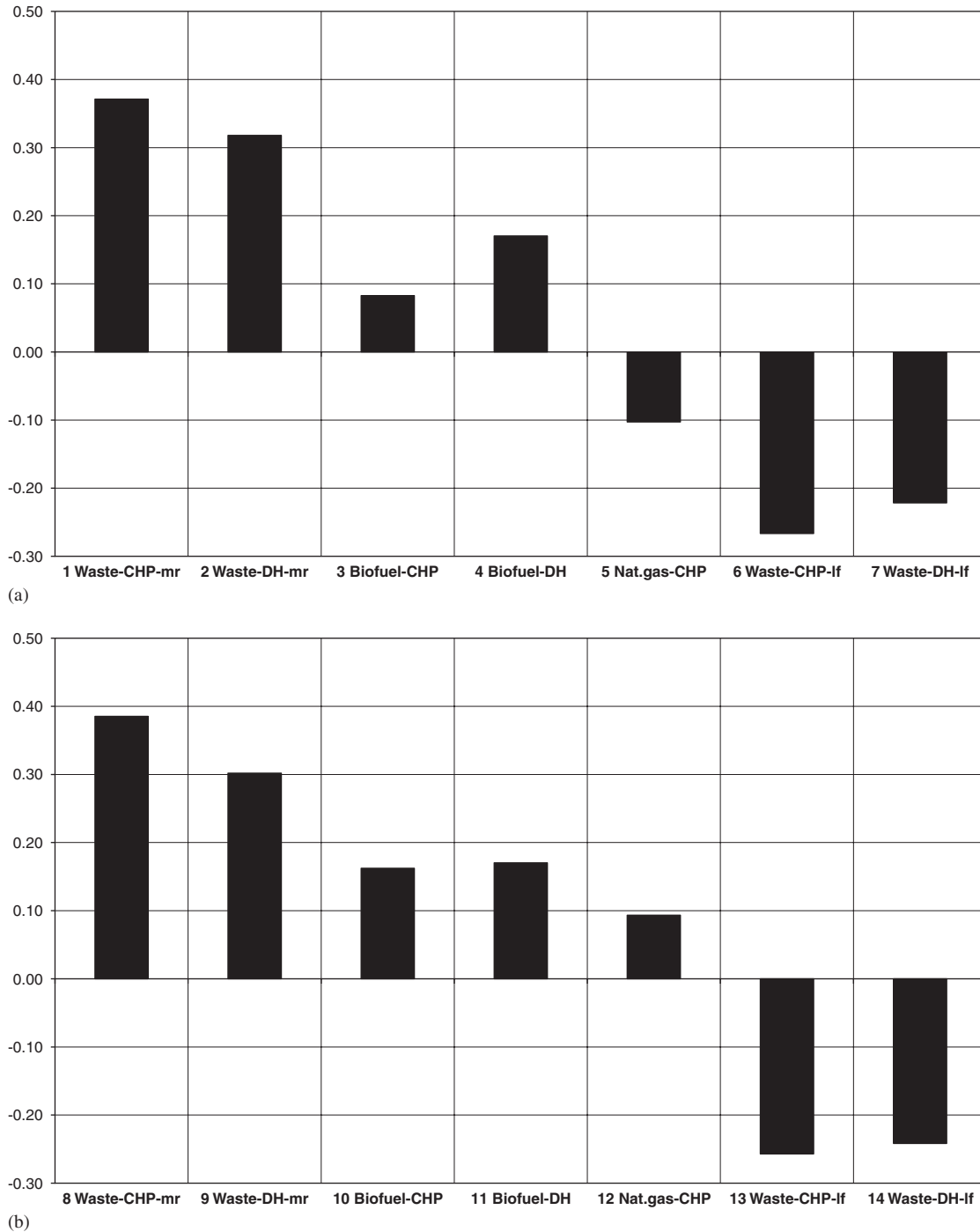


Fig. 7. (a) Weighted result for scenarios 1–7 (high environmental impact). Units in SEK/MJ heat. (b) Weighted result for scenarios 8–14 (low environmental impact). Units in SEK/MJ heat.

electricity system is also connected through transmission cables to other countries, such as Germany and Poland. This means that a change in the Swedish system can affect electricity production in countries outside the Nordic countries. The arguments concerning the large uncertainty in the marginal electricity production (see Section 2.3.2) and, hence, the conclusions of the study, are valid also in this context.

The results for waste incineration are very much dependant on the alternative waste management. Waste incineration is often (but not always) the preferable choice when incineration replaces landfilling. It is however, never the best choice (and often the worst) when incineration replaces recycling.

The results for natural gas are very much dependant on the marginal electricity production. If the marginal

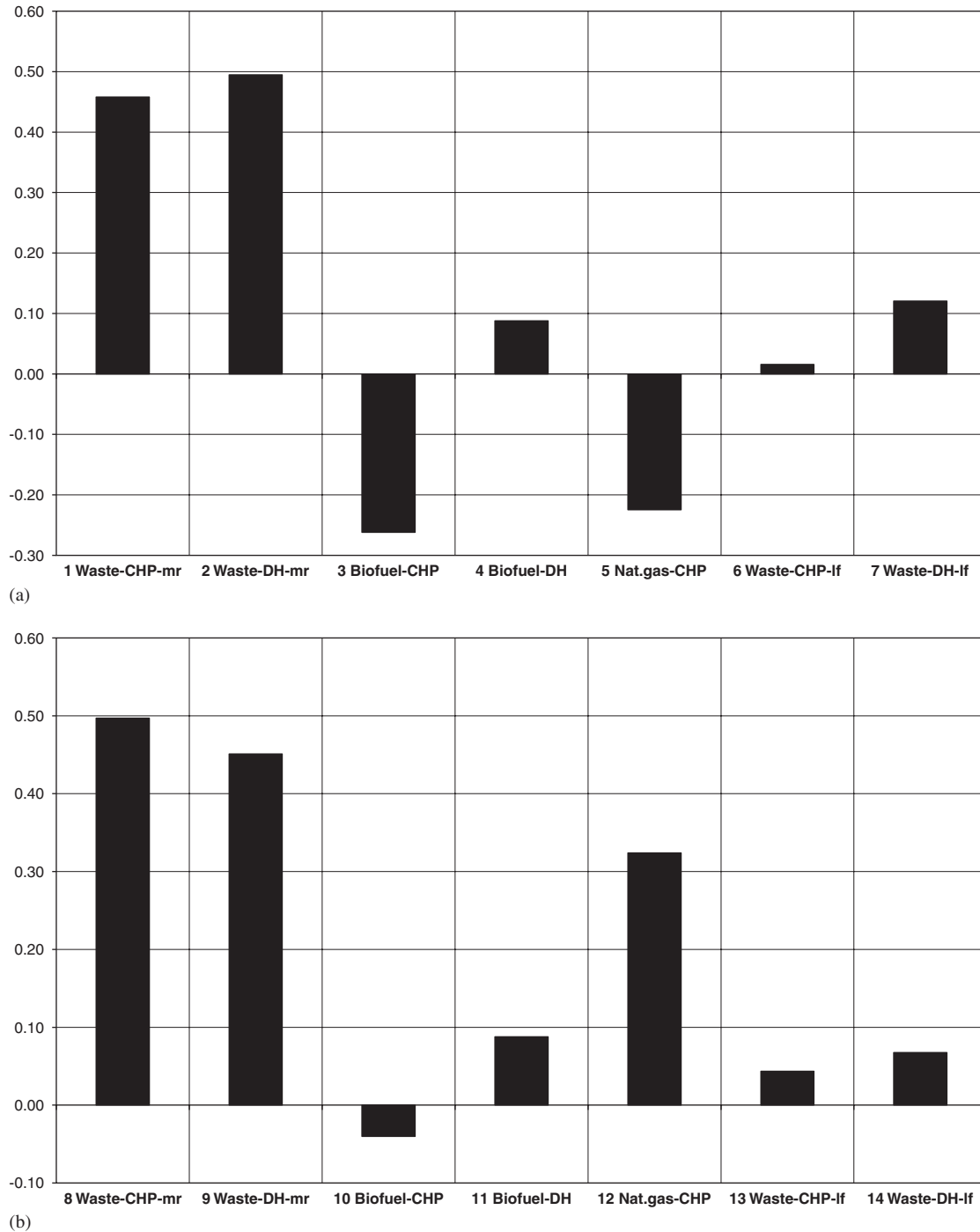


Fig. 8. (a) Weighted result for scenarios 1–7 (high environmental impact). Units in SEK/MJ heat. (b) Weighted result for scenarios 8–14 (low environmental impact). Units in SEK/MJ heat.

electricity has a high environmental impact, natural gas CHP replacing coal condense and natural gas condensing may be an interesting alternative and according to some weighting methods preferable over biofuels, especially over biofuels for DH. However, if the marginal electricity is mainly based on non-fossil sources, natural gas is in general worse than biofuels.

The results for both waste and natural gas as fuels are very sensitive to external factors such as waste management

and energy policies. The results for biofuels in CHP production are less sensitive to these uncertain, external factors, and indicate a net environmental benefit in eight out of 12 weighted results. This indicates that the support of combined production of district heat and electricity from biofuels is an environmentally robust strategy for Sweden. Our study does not include the possible use of biofuels outside the DH sector. It is not possible to conclude, based on our results, that CHP production is the best way to use

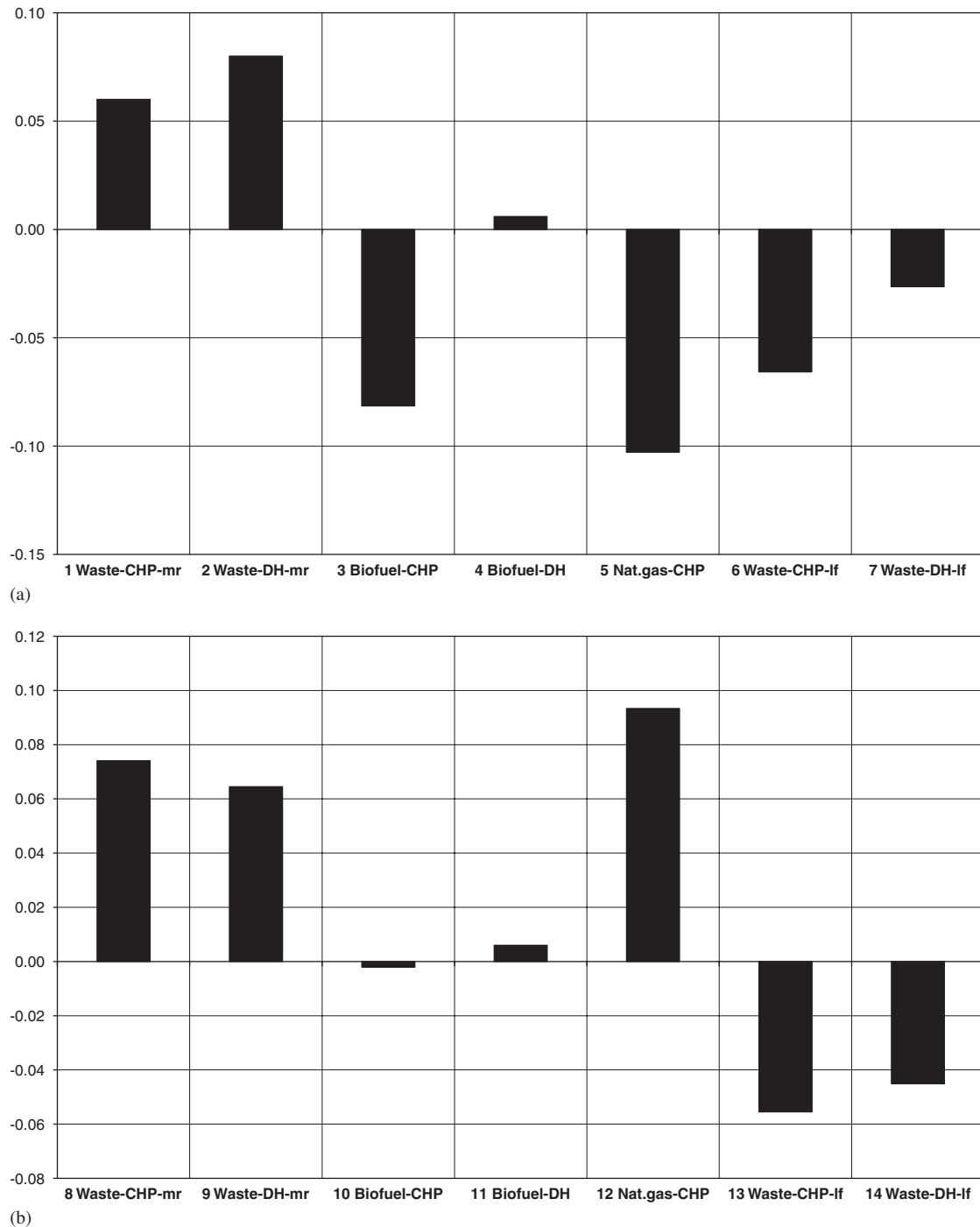


Fig. 9. (a) Weighted result for scenarios 1–7 (high environmental impact). Units in SEK/MJ heat. (b) Weighted result for scenarios 8–14 (low environmental impact). Units in SEK/MJ heat.

biofuels. But it is possible to conclude that biofuels is an environmentally valuable asset in the Swedish DH sector.

4.2. Methodology relevant conclusions

This study is an example of a consequential environmental systems analysis. It demonstrates how a dynamic

energy system model can be combined with an LCA. The normal practice so far in consequential LCAs have been to assume a specific electricity source as the marginal electricity, e.g. coal condensing power or electricity from natural gas. The results here demonstrate the sensitivity to the assumptions and thus the added value of combining a more sophisticated energy system model

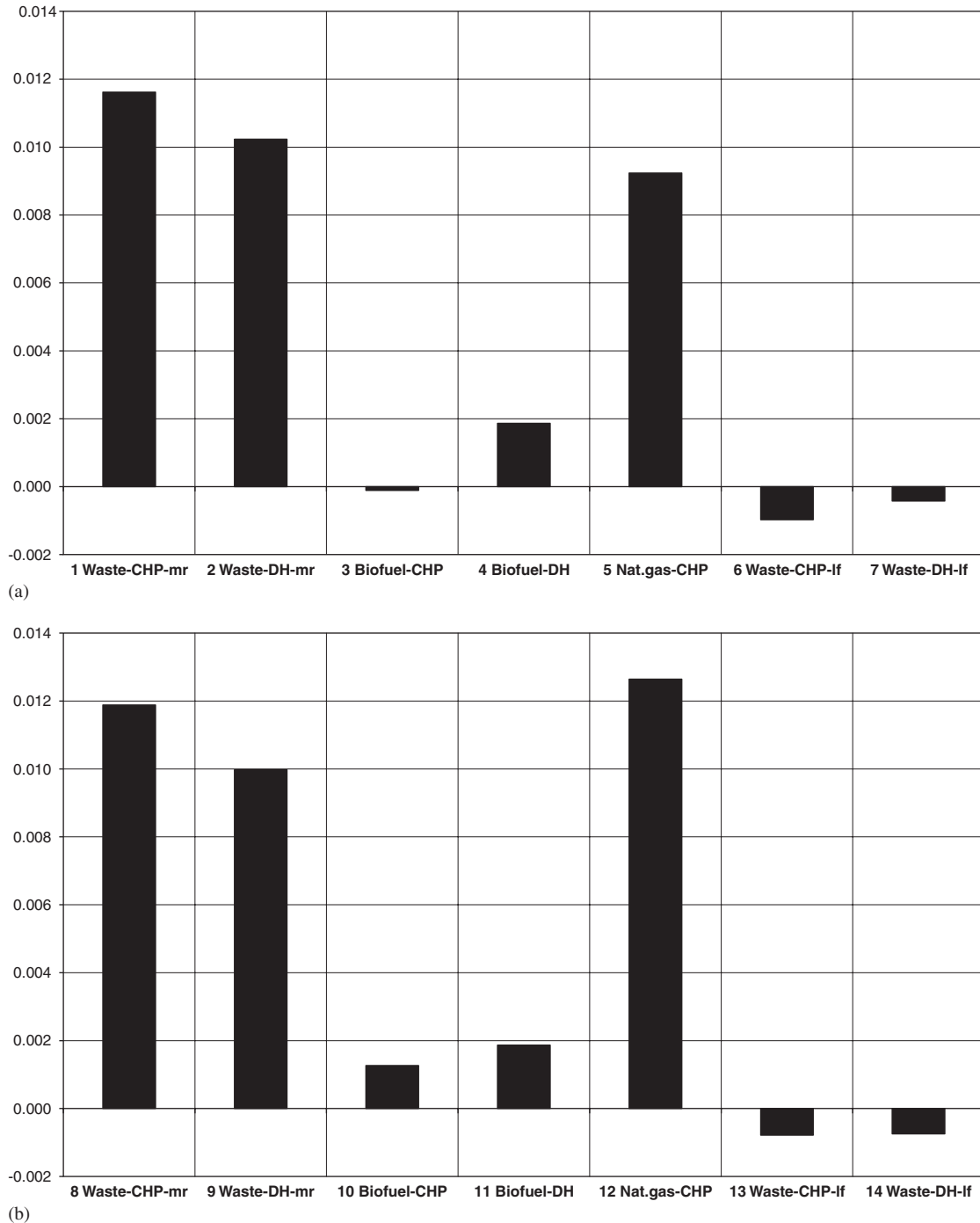


Fig. 10. (a) Weighted result for scenarios 1–7 (high environmental impact). Units in points/MJ heat. (b) Weighted result for scenarios 8–14 (low environmental impact). Units in points/MJ heat.

with the environmental assessment method. The electricity scenarios used in this study were independently developed and not strictly consistent with the purpose of our study. To ensure that the electricity scenarios are consistent with the rest of the systems analysis, it might be necessary to develop an energy systems model specifically for each environmental assessment. This would, of course, add significantly to the cost of the assessment.

This study also demonstrates how waste management can be modelled if waste as a fuel is to be compared to other fuels. It demonstrates the sensitivity of the results to the assumptions made concerning the alternative waste management.

The study also indicates the sensitivity of the results to the chosen weighting methods. This supports the tradition of using several weighting methods in parallel.

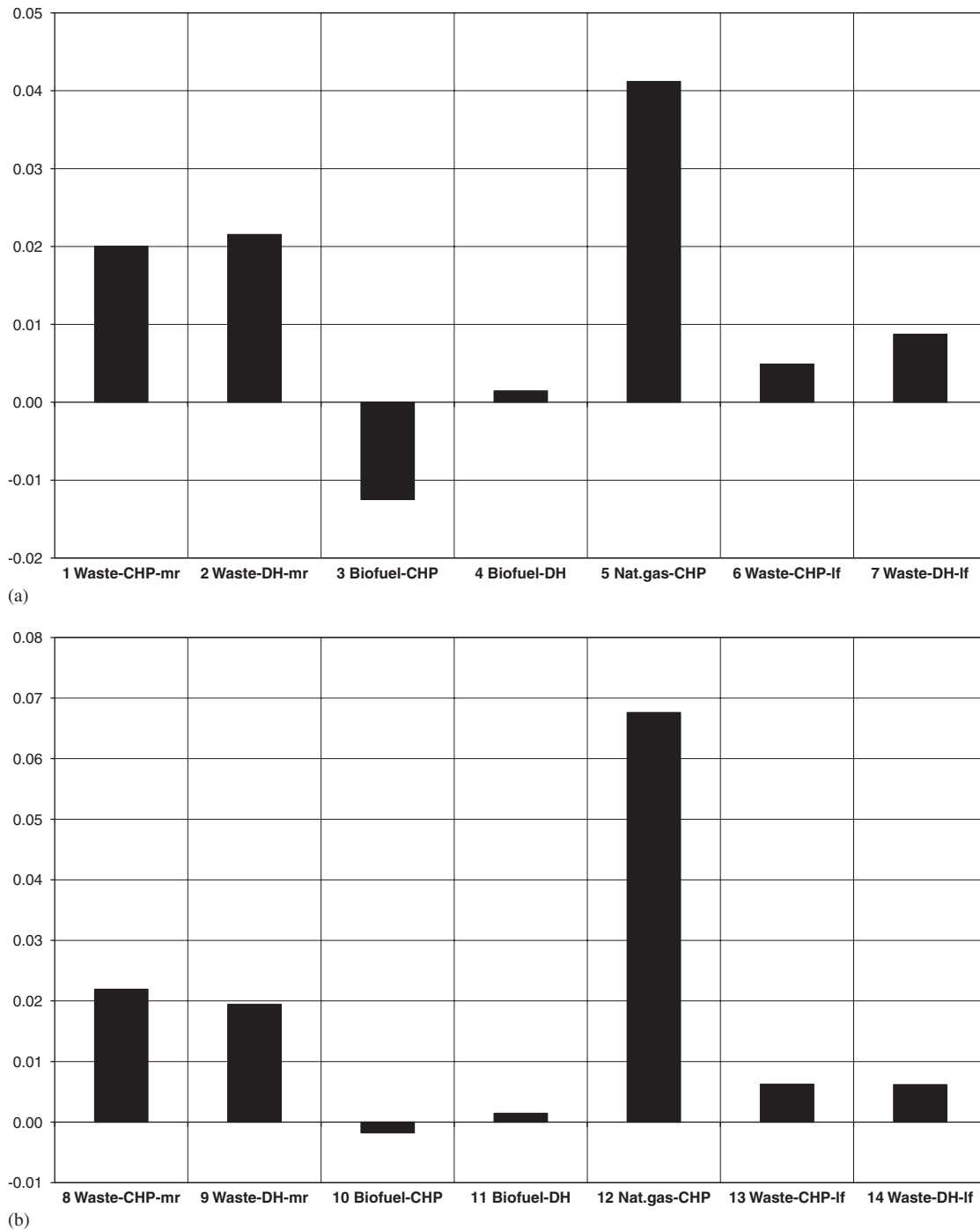


Fig. 11. (a) Weighted result for scenarios 1–7 (high environmental impact). Units in points/MJ heat. (b) Weighted result for scenarios 8–14 (low environmental impact). Units in points/MJ heat.

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