WASTE-TO-ENERGY SCENARIOS ANALYSIS BASED ON ENERGY SUPPLY AND DEMAND IN SWEDEN

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WASTE-TO-ENERGY SCENARIOS ANALYSIS BASED ON ENERGY SUPPLY AND DEMAND IN SWEDEN

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ABSTRACT

Energy recovery from waste treatment is of great significance for the waste management and sustainable energy supply. Sweden has proposed an ambitious vision of zero net greenhouse gases emissions by 2050, which makes most possible use of resources that the waste represents necessary. This paper is to study how the waste-to-energy (WtE) can interact with other forms of renewable energy to affect the energy supply and demand in Sweden. Based on an assumption of waste generation-treatment balance in 2050 with two cases, power preference and motor fuels preference, are investigated under diverse WtE scenarios. The results indicate that WtE production can contribute to the primary energy supply by 38 to 186 TWh, amounting to 6% to 47% of the total. The power production can be ranged from 7 to 35 TWh and motor fuels from 2 to 34 TWh through under different WtE scenarios. Furthermore, the final mitigation of CO_2 emission is estimated to be from 1 to 12 Mt in 2050 compared to base year of 2010, really depending on which WtE scenario is considered.

Keywords: waste-to-energy, scenarios, energy, waste treatment.

NONMENCLATURE

Abbreviation

BECCS	Biogenic carbon capture and storage
CCS	Carbon capture and storage
EU	European Union
GHG	Greenhouse gases
IPCC	International Panel on Climate Change
MP	Motor fuels preference
OECD	Organization for Economic Co-operation and Development
PP	Power preference
SCB	Statistics Sweden
SNG	Synthesis natural gas
TGC	Tradable green-certificate scheme
TEP	Tradable GHG emission permit
VAT	Value added tax
WtE	Waste-to-energy

1. INTRODUCTION

Municipal waste generated in the Organization for Economic Co-operation and Development (OECD) area has risen steadily from 1980 and exceeded 650 million tonnes (Mt) in 2006 (560 kg per inhabitant [1]. Two areas of great importance are how to achieve sustainable waste treatment and construct a sustainable energy system for our society [2]. However, the amount and the composition of municipal waste vary widely among different countries, being directly related to levels and patterns of consumption and also depending on diverse waste management practices. As a result, recycling and better usage of waste are of key importance to achieve the objective of significant and overall reduction of waste discharge, which contributes to preventing climate changes and mitigating the greenhouse gases (GHG) emissions. Further, the global use of energy, principally in form of carbon-based fuels, has risen remarkably in recent years, primarily due to the economic growth in countries like China and India [3]. Energy recovery from wastes is considered to be of social and environmental benefits. Furthermore, European Union (EU) legislation also encourages a change in the current waste treatment, which at present mainly consists of landfill sites. A cost optimization study concerning use of waste-to-energy (WtE) for the 2025 scenario in Denmark was made [4], which emphasized the important role of WtE on mitigation of CO_2 in the medium term future energy system. An extended study of WtE on optimization of both investments and production of power, heat and biofuels was given in [5] for a future possible energy system in 2025, which covered the Northern European power market (Denmark, Norway, Sweden, Finland and Germany). Another similar study [6] concerned how the WtE could contribute to the reduction of 18 Mt CO_2 under different scenarios in Japan if the fossil fuels were replaced by the energy from waste in the future. WtE scenarios were also proposed by [7] to have a low waste intensity in coming decades in Sweden. Other four WtE utilization scenarios were developed in [8] using both qualitative and quantitative methods to assess the waste for energy use based on surveys of engineers and church representatives. The results were much relevant to the WtE policy making circle and a higher integration of waste energy into the existing energy supply situation then the present would be economically and socially worthwhile. An overview for exploring the possibilities of energy generation from municipal solid waste was investigated in Indian scenario to tackle problems of the waste management and energy crisis in the coming years [9]. However, most of previous studies paid much attention to the waste management or how to use waste for energy use without considering the combination of changes of waste generation and energy supply/demand in the coming decades. In addition, how the WtE can contribute to the future energy supply/demand is not studied much at present.

This paper focuses on the prospective scenario analysis of WtE through combining different waste and energy scenarios, and how it can contribute to satisfying the future energy supply/demand in Sweden. The objective of this paper is to provide quantitative overview of energy production from waste and increase use of waste for energy purpose in Sweden.

2. METHODOLOGY

The methodology used for the study is illustrated in ***Fig. 1***. The present status of energy demand and supply, and waste generation and treatment is analyzed and evaluated. Then an inventory of energy and waste generation scenarios are made to analyze the maximum potential energy recovery from the waste treatment in the coming years of 2010-2050 considering the possible changes of policies and technologies.

A basic waste generation-treatment balance is assumed by 2050 through maximization of WtE use which means a target when all the generated wastes possible for energy production are treated sustainably and completely by multi-technologies with a maximum energy output under different scenarios. Two cases are considered for WtE production under all scenarios except the baseline scenario: power preference (PP) and motor fuels preference (MP). The difference between two cases is given more priorities to which production, power or motor fuels, in the future. The analysis of WtE scenarios refer to the waste generation scenarios respectively combined with energy scenarios to determine how the WtE can contribute to the future energy supply and demand in Sweden. Time steps of five year are considered from 2010 to 2050 to show the results but the calculations between these points are also made for a continuous change as the basis for analysis.

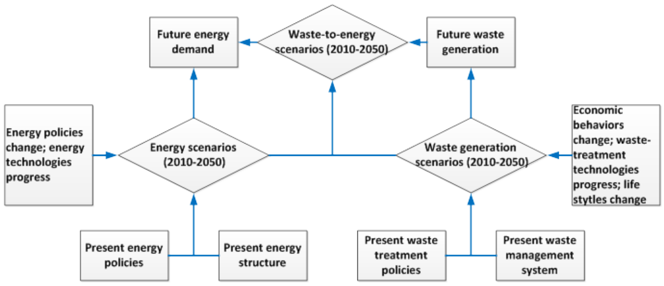

Fig. 1 Methodology flow chart in this study

2.1 Waste for energy

Wastes utilized for energy purposes in this study are animal and vegetable waste, household waste, wood waste, water waste sludge, agricultural straws and forestry waste like barks and sawdust, excluding waste for reuse and recycling, and waste from pulp and paper industry like black liquor. The included waste is optionally used for production of power, heat, and motor fuels like biogas, syngas or ethanol through different technological conversion processes. However, the collected landfill biogas is excluded from the final WtE production calculation.

2.2 Calculation of waste generation and WtE production

Waste generation under different waste scenarios is calculated with the methodology described in [10]. The WtE production calculation is based on different energy supply and demand under different energy scenarios.

2.3 Data preparation

The data is prepared through the following ways: macro statistical data is taken from external sources, such as Statistics Sweden (SCB), Swedish Energy Agency, Swedish Environmental Research Institute and Swedish Waste Management; waste treatment data is collected at case plants or calculated through operation data from representative treatment plants in Sweden, for example waste heating plants; further some data is collected from pilot plants, for example of ethanol production from cellulosic materials; and from published literature.

2.4 Motor fuels

In this study, motor fuels production from waste refers to biogas production by digestion, syngas production by gasification and ethanol as an alternative to replace the gasoline or diesel in the transportation sector. Other forms of motor fuels processed from the intermediate of biogas or syngas are calculated by the equivalent biogas or syngas amount relating to energy content.

2.5 Evaluation of CO_2 reduction

Regarding the fact that in Sweden the majority of the heat is already provided by power, biofuels, WtE, waste heat and other forms of renewable energy and only a small part comes from fossil fuels, mainly the operation of oil-fired boilers in the peak demand time, only the possible CO_2 reduction from the added power and motor fuels production compared to the base year 2010 is included in this study. The reduction of CO_2 emission from added power production is considered to be 350 kg/MWh in this study, based on an assumed natural gas combined cycle power plant [11]. As for the motor fuels, an average reduction of 242 kg/MWh is adopted [12]. However, the fossil-origin CO_2 emission from waste combustion must be removed from the reduction calculation. In addition, because the UNFCCC doesn't publish the official data about CO_2 emission in 2009 and 2010 by countries until Dec. 2011, a same reduction percentage as 2008-2009 will be applied on the period of 2009-2010 for Sweden. If so, Sweden will roughly have a CO_2 emission about 46.67 Mt in 2010.

3. PRESENT ENERGY STRUCTURE

At present, fossil fuels like coal, oil and natural gas are still globally predominant over other forms of energy carriers in the primary energy supply. There is a breakdown of energy use over the world in 2008, see ***Fig.2***.

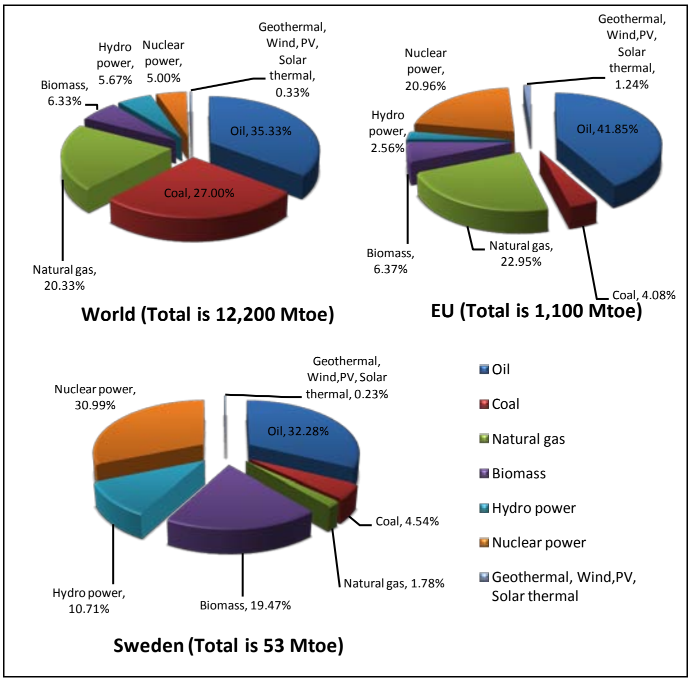

Fig. 2 Information of energy supply in 2008 for the world, EU and Sweden

Source: IEA ; Eurostat and [13,14]

Note: biomass part in Sweden includes biofuels, peat and energy from waste.

If one share of oil is consumed, when taking into account all energy use, an equivalent of three shares of oils will be used totally. Statistically, about 88% of the total energy use comes from the exhaustible resources while only a little more than 12% is from the renewables. While in EU, its energy consumption is characterized with a much higher share of nuclear power, of which a big contribution is from countries like France and Sweden, but a dramatically lower share of coal than the global average, see ***Fig.2.*** In Sweden, about one-third of the primary energy supply is from renewable sources and a big share of nuclear power also exists, even much higher than the EU average, see ***Fig.2***. However, if considering the energy changes over the past two decade, the proportion of nuclear power has decreased steadily since 1990, whose decrement is offset by the bioenergy from peat, waste and other kinds of biofuels. The share of renewable energy has been doubled compared to 1990, which signals a trend of renewable energy increase in the primary energy supply for the coming decades. Another protrudent phenomenon is the general decrement of total primary energy supply after 2001 and it hits the recent twenty-year bottom in 2009. The energy supply from hydro power and crude oil or its related products are very stable over the recent years, the latter of which is mainly consumed in the transportation sector. For coal, the use has decreased continuously to 18 TWh in 2009 from 31TWh in 1990 [15].

4. FUTURE ENERGY CHANGE IN SWEDEN

The Swedish energy mix has undergone dramatic changes compared to what it was twenty years ago. Firstly, despite the rhetoric of a ”nuclear renaissance” recently in Sweden [16], more nuclear reactors will be duly shut down permanently because of the nuclear-power phase-out policy passed by a Swedish referendum in 1980 [17]. A foreseeable decrease in nuclear power generation will provide a possible increase in power production from renewable energy sources and waste in Sweden. Secondly, the share of biogenic motor fuels will experience a stable growth in the near future. At present, blended petroleum with a certain proportion of ethanol, for example E5, with 5 % of ethanol, and E85, with 85 % of ethanol, is common in Sweden and the use of ethanol will have better economy if its price per liter is below 74% of petroleum [18]; the use of biogas and syngas or their upgraded products will also experience an increase in the transport sector [13]. Thirdly, despite of the small share of coal use, the use is still shrinking because of the tradable green-certificate scheme (TGC) in Sweden existing since 2003 and the tradable GHG emission permit (TEP) scheme introduced in EU from Jan. 1 of 2005 [19]. Fourthly, renewable energy such as solar energy, wind power, geothermal energy, etc are foreseen to increase quickly but will probably not bear the major burden of sustainable energy sources in the near future use [20].

4.1 WtE policies

At present, there are two strongest driving forces that will have a long-term impact on the future energy recovery from waste: decrease in landfill treatment (Directive 1999/31/EC) and increase in the share of renewable energy (Directive on promotion of energy from renewable sources)

[21]. In March 2007 the EU's leaders endorsed an integrated approach to climate and energy policy with the aims to reduce global warming, ensure EU's energy supply security and strengthening its competitiveness. To kick-start this process, a series of binding climate and energy targets to be achieved by 2020, known as the "20-20-20" agenda, have been set. These are:

- 20% reduction of GHG emissions below 1990 levels;
- 20% of EU energy use from renewable resources;
- 20% reduction in primary energy use by improving energy efficiency.

As considered by the EU administration, the WtE can pose a great contribution to the fight against global warming which now can be quantified through International Panel on Climate Change (IPCC) in the framework of the UN convention of Climate Change. As reportedly estimated, there is a potential up to 43-80 Mt/year of CO_2 emission reduction from WtE use in EU [22]. As a member of EU, the promotion of WtE is always a component of the Swedish government's strategy to construct long-term sustainable waste-treatment and energy-supply systems. Sweden has reduced the GHG emissions by 34% from 1990 to 2006 and the reduction is expected to be 76% by 2020 [23]. In Sweden, decreasing the amount of waste to landfill treatment is implemented by imposing a rising tax, from 250 SEK/t in 2000 to 435 SEK/t in 2006; introducing a ban on landfill treatment of biowaste in 2005 [24]; increasing the biogas production through anaerobic digestion of household waste by introducing the certification system [24] ; supporting the heat or/and power production from waste combustion by abolishing the taxation on it from 2010; stimulating renewable power production by providing subsidy through a Green Electricity Certificate System from 2003 [13], covering municipal solid waste treated by combustion for the power production. Similar to most other countries over the world, the transport sector is also using a very high proportion of fossil fuels compared to other sectors in Sweden. Therefore, finding alternatives to reduce the dependency on the imported fossil fuels in the transport sector is very important to reduce the general GHG emissions in Sweden. In 2009 the percentage of renewable motor fuels amounted to 5.4% about 4.6 TWh [13] while it was 4.9% about 4.3 TWh in 2008. The alternative motor fuels that are at present used for vehicles are mainly natural gas, biogas, ethanol and FAME, of which biogenic-origin fuels can be exempted from taxation.

4.2 Energy scenarios

Energy scenarios analysis is important to be able to describe possible development paths. A summary of available energy scenarios is made in ***Table 1***. Although a "Baseline Scenario" is given to reflect a continuation of current trends and policies [25] only until 2030, an extension of the time horizon to the year 2050 is assumed in this study. The two scenarios "Energy Revolution Scenario" and "Advanced Energy Revolution Scenario" concentrate on technical progress to improve the energy efficiency and decrease the specific unit investment[1] of renewable energy like solar power, wind power, geothermal power and bioenergy as a result of an assumption of high fossil fuels prices, see ***Table 1***.

Table 1 Comparison of energy scenarios considering energy supply and demand in Sweden

No	Scenario name	Description
1	Baseline Scenario [26] with a focus on current status	Total energy supply will increase slightly in the coming decades to year 2050 based on demand, see ***Fig. 3***. Trends and policies in 2008 continue until 2050. For example, energy tax is not imposed on fossil fuels used in manufacturing, forestry, aquaculture and agriculture and only 21% of carbon tax is charged for these industries. Ethanol, methyl ester, biogas are exempted from energy and carbon tax. The CO_2 permit price 30€/t is considered constant for a long-term level in the covered period.
2	Energy Revolution Scenario [25] with a focus both on technical progress and energy efficiency.	Total energy supply will decrease continuously until 2050 with a decreasing demand, see ***Fig. 3***. High fossil fuel prices are assumed compared to the market price in 2009. For examples 124 €/barrel for crude oil in 2030; 21.54€/GJ for natural gas in 2050; 142.59 €/t for hard coal in 2050. However, a stable but slight increment for biomass price to 8.7 €/GJ in 2050 is assumed.
3	Advance Energy Revolution Scenario [25] with a focus both on technical progress and energy efficiency.	Total energy supply is similar but a lower specific investment cost for renewable energy is obtained, compared with the "Energy Revolution Scenario"
4	Biofuels 2050 Scenario [28] with a focus both on biofuels and power in transport.	Low total energy supply changes between 2005 and 2050. 50% of energy demand for transport is met by power and the other 50% by biofuels.
5	Fossil fuels + BECCS 2050 Scenario [28] with a focus on CCS.	Low total energy demand changes between 2005 and 2050, see ***Fig. 3***. 50% of energy supply for transport is met by electricity and another 50% by fossil fuels. BECCS can compensate the continued use of fossil fuels.
6	Renewable Energy Scenario [27] with a focus both on renewable energy and energy efficiency.	Total energy supply is reduced by 33% in 2050, compared to 2010. An energy system is described as a resource-efficient energy system with -0.5% yearly growth of total energy demand for each industry sub-sector except pulp and paper industry. However, the coal used in steel industry is excluded from the coverage.

[1] Specific unit investment means money invested for a unit energy production, for example €/MWh.

A study on barriers and opportunities to achieve a low-carbon energy system is done by analyzing two scenarios: “Biofuels 2050” and an alternative scenario “Fossil fuels + BECCS [2] 2050”. “Biofuels 2050” is characterized by extensive introduction of biofuels in the transport sector while in the “Fossil fuels + BECCS 2050” continued use of fossil fuels in the transport sector is assumed [28]. To reach the same low carbon dioxide emissions as in the first scenario carbon capture and storage (CCS) of biogenic CO_2 emissions is applied. The energy scenario “Renewable Energy Scenario” aims at providing almost 100% of the energy demand by renewable sources with a basis on measures to improve energy efficiency, for example biorefinery systems. No matter what kind of measures for energy efficiency improvement and renewable energy production are discussed in the above-mentioned scenarios, a shift from road to rail for goods transport and the use of municipal waste for energy purposes should be given priorities in all available scenarios. Except for the “Baseline Scenario”, the other scenarios have assumed a decrease of the total energy supply at different rates from 2010 to 2050, see ***Fig. 3***, as a result of diverse measures to improve energy efficiency and develop renewable energy units.

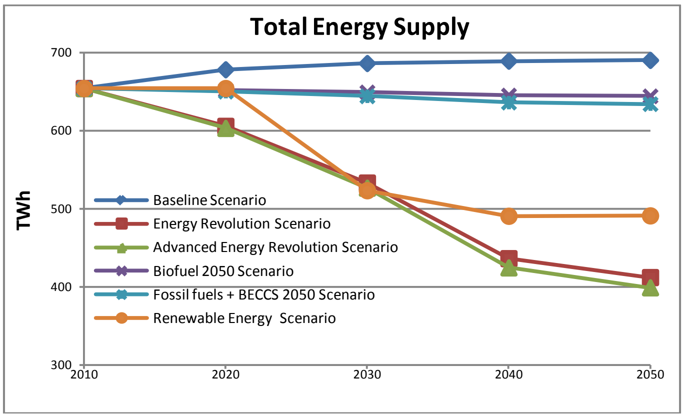

Fig. 3 Total energy supply under different scenarios in Sweden [25,26,27,28]

Note: Assumptions are the same as references except the baseline changed into 2010 in all scenarios.

5. WASTE FOR ENERGY PRODUCTION

5.1 WtE technologies

In EU, landfill, combustion and biological treatment are the most commonly used technologies for local waste treatment. The selected technologies included in this study represent the technologies to convert biomass and waste to energy products such as power, heat, motor fuels.

Combustion of waste, potentially mixed with other materials for co-firing, in a plant principally constructed for energy utilization is a sustainable way to treat the combustible content of municipal solid waste. As for the anaerobic (oxygen-free) digestion of biowaste, which includes organic waste from household and industry, sewage sludge, manures from the farms and other biowaste like energy crops and their residues, with biogas production, is a mature technology in Sweden [29]. The biogas plant can be combined with a heating plant or combined heat and power plant for heat or power and heat productions. Furthermore, the raw biogas could be upgraded into motor fuels for municipal public transport and the residue of digestate acts as a nutrition material for the land soil. In addition, gasification of biogenic origin materials, mainly generates synthesis natural gas (SNG) through pyrolysis, partial oxidation and hydrogenation processes. The gas can be used in heating plants or combined heat and power plants. SNG can also be further processed to other chemicals and biofuels such as methanol, DME, and hydrogen, all of which could be used as motor fuels [30]. This is a technology under development and in 2011, there are nine pilot gasification plants in Sweden and more plants are being constructed. Another technology for motor fuels production is the ethanol produced from the agricultural and forestry waste or cellulosic waste, called 2nd-generation of ethanol production. It can become a promising alternative to motor fuels from energy, cost and environmental perspectives. A good strategy to increase energy efficiency and decrease the production cost is to integrate the cellulosic ethanol production with a combined heat and power plant [31, 32]. Considering the rich cellulosic sources in Sweden, this technology has a big potential for increasing the flexibility in the future motor fuels supply.

5.2 Availability of waste for energy production

The proportion of bioenergy used in the Swedish energy system is already about 20% of the total energy supply [13]. Most of them are indigenous biofuels, peat and waste, consisting of forestry wastes, like bark, chips, return timber; processed products, like pellets and briquettes; biogas from biowaste produced by digestion; and bioethanol blended with gasoline. The potential waste available for energy utilization is summarized in ***Table 2*** for the year 2010 as the baseline for the scenarios development.

Table 2 Waste available for energy use 2010

Waste type	Generation (Kt)	Optional processes for energy use
Animal and vegetal wastes	4704	Digestion
Household wastes	2665	Combustion, digestion
Sludge	2099	Digestion
Wood wastes	377	Combustion, fermentation, gasification
Agricultural straw	540	Combustion, fermentation, gasification
Forest waste	17110	Combustion, fermentation, gasification

Source: [33, 34, 35, 36]

How the waste generation will change until 2050 is given in ***Table 3*** for five waste generation scenarios excluding the agricultural straws and forest wastes. How the assumed five

[2] BECCS means capture and storage of biogenic carbon dioxide.

waste generation scenarios influence the waste amount for energy use is presented in further detail by [10]. The agricultural straw is dependent on the food consumption so it is closely related to the population growth. In this study the agricultural straw is assumed to have the same growth rate as the population from 2010 to 2050, which is estimated by Statistics Sweden (SCB) [15]. Forest waste refers to the sawdust and barks in forestry industry and changes at the same average rate as wood waste until 2050 but never exceeds the maximal potential estimated by [36].

Table 3 Waste intensities over 2010 to 2050 (yearly growth %)

Item	Baseline	Global sustainability scenario	Global markets scenario	Regional markets scenario	European sustainability scenario
Animal and vegetal wastes	0.83	0.2	2.1	0.76	0
Household wastes	0.38	1.5	5.8	3.3	0.4
Sludge	2.0	2.0	3.4	1.6	1.8
Wood wastes	0.5	-1.5	1.9	1.3	0.4
Agricultural straw	0.6	0.6	0.6	0.6	0.6
Forest waste	0.5	-1.5	1.9	1.3	0.4

Source: [15,33,36]

Note: Assumptions are the same as the reference sources except that the base year is changed into 2010 and the time horizon is extended to 2050.

6. RESULTS AND DISCUSSIONS

6.1 WtE production

Most of the wastes will experience a more or less growth in the coming decades except wood waste and forest waste in the waste scenario of ”Global sustainability”. The waste scenario of ”Baseline” is estimated based on the consistency with the long-term past development in Sweden, which is roughly in proportion to the personal consumption and macro-economic growth.

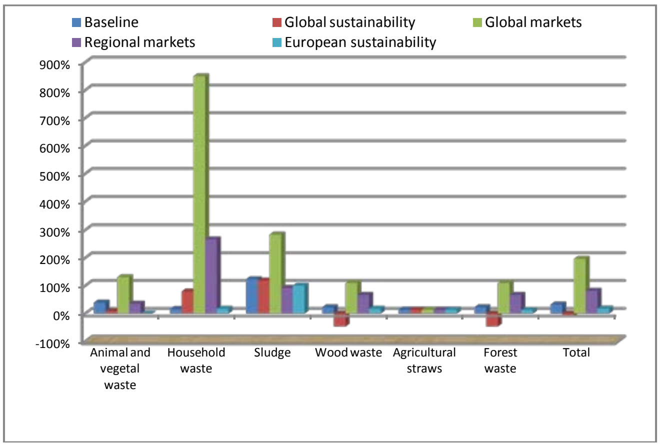

Fig. 4 Percentage changes of waste generation 2010-2050 (only including the waste possible for energy production use) [33]

The total amount of included wastes will grow up to 82 Mt in 2050 in the waste scenario of “Global market”, almost two times as much as 2010, while for the waste scenario of ”Global sustainability” it will drop by 11% to 25 Mt in 2050, see ***Fig. 4***. They actually represent two extremes about waste generation until 2050. The total WtE production under the listed waste scenarios, mainly in forms of energy carriers of power, heat and motor fuels, are illustrated by the ***Fig. 5*** and ***Fig. 6*** for the two cases for the WtE utilization. The PP cases for all scenarios usually have higher gross energy output than the corresponding MP cases, which means that the WtE always has a higher efficiency for the power production than the motor fuels if the raw materials are optional for both productions. The detailed energy production for three energy carriers is plotted for the period of 2010 to 2050 in ***Fig. 6***. The PP case is always characterized with more heat production than the MP case because the power production is always accompanied with higher proportion of heat output than the motor fuels production. However, which case is preferred in the energy scenarios is really depending on the demands of the different energy carriers.

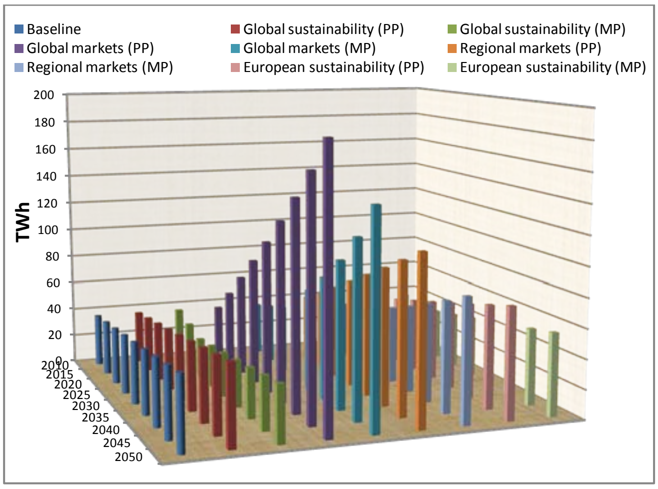

Fig. 5 Development of total WtE production under different waste scenarios with two cases for the waste to energy utilization, power preference (PP) and motor fuels preference (MP)

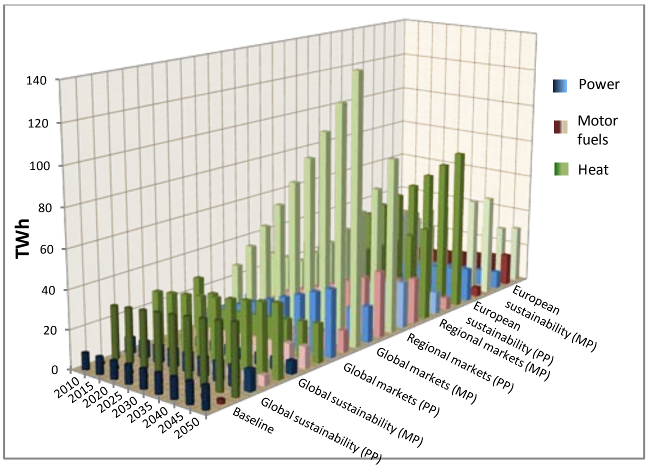

Fig. 6 Development of WtE production in energy carriers under different waste scenarios with two cases for the waste to energy utilization, power preference (PP) and motor fuels preference (MP)

6.2 Contribution of WtE to future energy supply and demand

The total energy supply changes have been shown in ***Fig. 3*** for all the energy scenarios from 2010 to 2050. If no tremendous changes happen in the present WtE related policies and systems, the percentage of WtE production in total energy supply will ascend little by little from 5.6% in 2010 up to 7.3% in 2050 under the baseline scenario, see ***Fig. 7***. If the nuclear power phase-out policy continues, the power gap caused by the decrement of nuclear power must be offset by other renewable sources, of which the municipal waste can get a more important role than present [21].

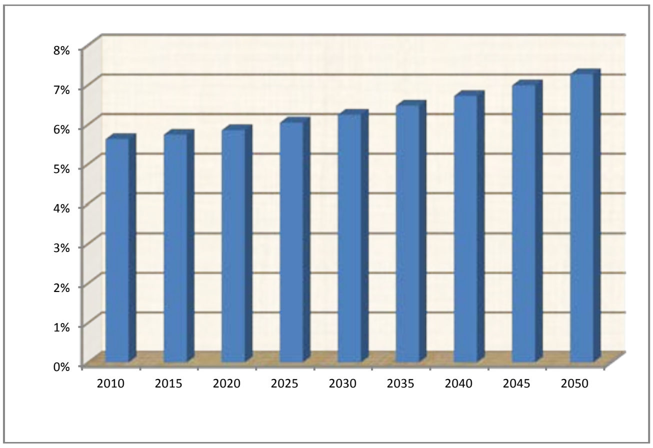

Fig. 7 Development of percentage of WtE production in total energy supply under baseline scenario

However, the demands for different energy carriers behave in another manner rather than the total energy supply, see ***Fig. 8***, which really depends on the future change of energy use and how the energy policies can affect renewable energy production.

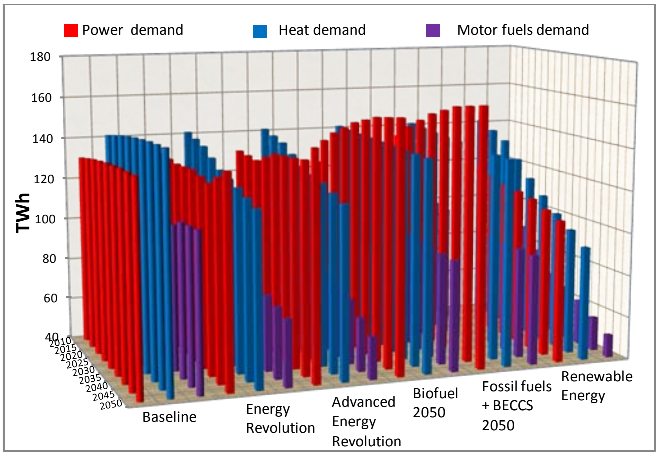

Fig. 8 Development of power, heat and motor fuels demand from 2010 to 2050 under different energy scenarios

For examples, in the energy scenarios of "Energy Revolution" and "Advanced Energy Revolution", the decrement of specific investment and production cost for the renewable energy will boost the applications of solar power, wind power, bioenergy, geothermal energy, etc.. In addition the scenario of "Fossil fuels + BECCS 2050" has assumed a commercial application of CCS technology in the bioenergy systems, which can generate a negative CO_2 emission as a trade-off to keep the continued consumption of fossil fuels before 2050. Together with "Biofuel 2050", they both have set a target of 50% share of power in the transport sector. This relieves the pressure on the non-fossilization of motor fuels, which is why the total energy supply in these two scenarios doesn't change so much from the baseline scenario but a much higher power demand appears, see ***Fig. 8***. Compared to these two scenarios, a lower share of power in the transport, but still much higher than in the baseline scenario, is required in the energy scenarios of "Energy Revolution", "Advanced Energy Revolution" and "Renewable Energy", which help reduce their demand of motor fuels. Another notable contribution is from the improvement of energy efficiency for the energy production and consumption.

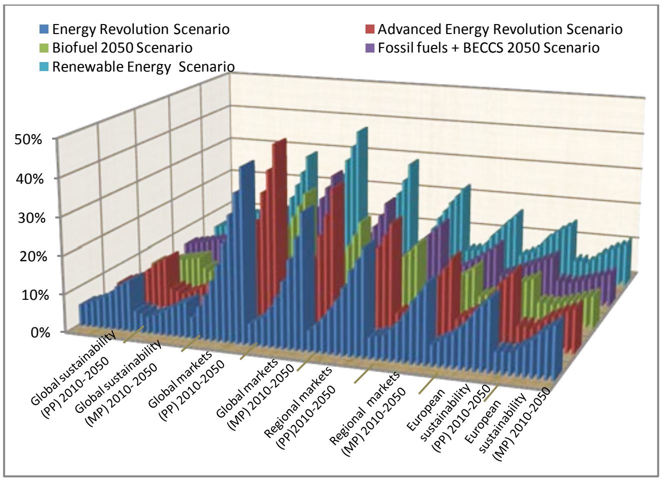

Fig. 9 Development of percentage of WtE production in total energy supply under different energy scenarios with two cases for the waste to energy utilization, power preference (PP) and motor fuels preference (MP).

How much the WtE production can contribute to the total energy supply could be found in detail for the two cases in ***Fig. 9***, including forty WtE scenarios in total when the waste scenarios are combined with the energy scenarios, except the baseline scenario, respectively. The contribution of WtE in 2050 can be up to 45% or 47%, "Global markets (PP)" combined with "Energy Revolution" or "Advanced Energy Revolution", and both down to 6%, "Global sustainability (MP)" combined with "Biofuel 2050" or "Fossil Fuels + BECCS 2050". The latter two are very close to the baseline scenario but have a different energy consumption structure. Considering the contribution of WtE to different energy carriers in baseline scenario, the shares in the motor fuels, power and heat can only rise from 1%, 6% and 17% in 2010 to 2%, 8% and 22% in 2050 respectively. In fact, the indigenous motor fuels from municipal waste are often produced in form of biogas, mainly used in public transport and district heating system. Other forms of biofuels, like FAME from energy crops of rapeseed and ethanol imported from Brazil, act as permissible admixtures in traditional fossil fuels. All of them aim to reduce the share of fossil fuels use in the transport sector.

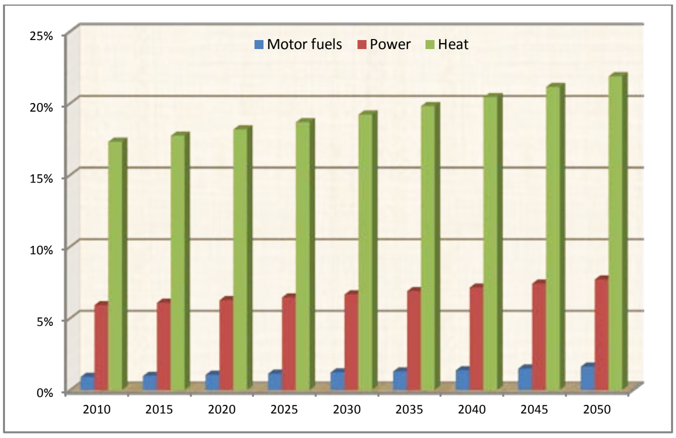

Fig. 10 Development of percentage of WtE production for different energy carrier demand under baseline scenario

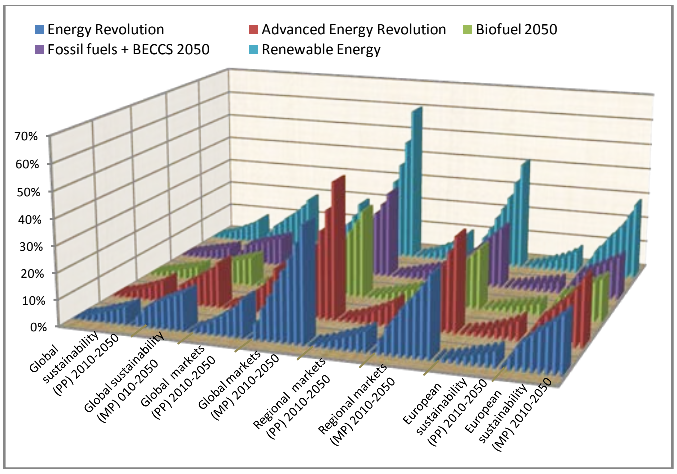

Fig. 11 Development of percentage of WtE production for motor fuels in total demand under different energy scenario (10% of conversion and distribution loss is assumed)

However, a diversification in the motor fuels supply will surely take place in the coming decades, which is comprehensively influenced by many complex factors, such as technical development, consumption habits, education and stimulating policies. In the energy scenarios of "Biofuel 2050" and "Fossil fuels + BECCS 2050", half of the total energy for transport is assumed to be power. However, in the energy scenario of "Renewable Energy" part of the transport activity on roads is replaced by rail transport and higher energy efficiency is achieved, which causes a general reduction of energy demand in the transport sector from 98 TWh in 2010 to 51 TWh in 2050, but with an increase of power share. When the energy scenario of "Renewable Energy" together with different waste scenarios forms into WtE scenarios, they always have the highest ratio of WtE to the total energy demand in the transport sector.

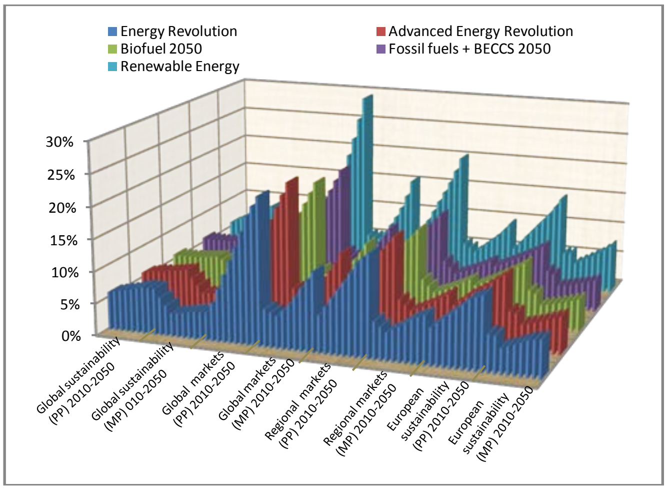

Fig. 12 Development of percentage of WtE production for power in total demand under different energy scenario (10% of conversion and distribution loss is assumed)

The energy scenarios of "Biofuel 2050" and "Fossil fuels + BECCS 2050" have the highest power demand compared to the other energy scenarios, see ***Fig. 8***, leading to two the lowest WtE proportions of 4% to the total power demand under the WtE scenarios of the combination with "Global sustainability (MP)" in 2050. As proposed by the [7] for a WtE scenario of biofuels with low waste intensity, the combination of "Biofuels 2050" with "Global sustainability" should be prioritized over the others. The PP case have a 6% in power demand and 5% in motor fuels demand from WtE production while the MP case changed into 4% and 11% respectively. As suggested in energy scenarios, a fossil-fuel-free transport system needs a big shift for transport from road to rail. Other forms of renewable energy will have more shares in the transport sector, which is described in the energy scenario of "Renewable Energy", where the wind power, solar power and bioenergy as well as the existing hydro power will be the "four bigs" and amount to over 80% of the total energy supply by 2050.

6.3 Contribution of WtE to CO_2 reduction

The total added amount of CO_2 mitigation from 2010 by replacing fossil fuels counterparts in all waste scenarios are summarized in ***Fig. 13*** through maximizing the energy output in two cases until 2050. However, little difference is between the two cases of PP and MP if heat is excluded from the calculation. Reportedly estimated by the Guardian [37], a total of CO_2 emission in Sweden in 2009 is roughly 51 Mt. For the baseline scenario, it can reduce 1 Mt in 2050, about 3% of total CO_2 emission in 2010. However, in waste scenarios of "Global markets", a contribution of 12 Mt of reduction could happen in 2050, about 29% reduction from 2010 in the two cases, respectively. These two extremes can roughly range the potential contribution of CO_2 mitigation from WtE use in the next decades.

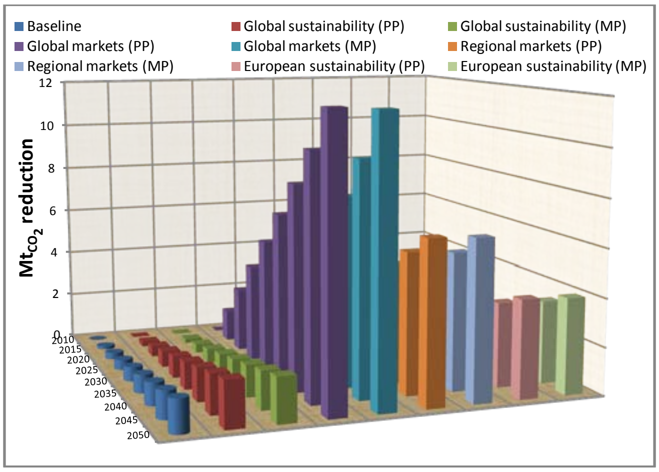

Fig. 13 Development of CO_2 reduction with WtE production to replace fossil-fuel-based power and motor fuels under different waste scenarios (excluding fossil-origin CO_2 in waste combustion)

7. LIMITATIONS

This study only focuses on the mass and energy balance during different WtE technical processes. Detailed technical requirements and economic feasibilities are excluded from this study. How the WtE can contribute to the energy supply to meet the future demand as discussed in this paper should be a part in the future research work.

8. CONCLUSIONS

The waste-to-energy scenarios are created through combining the waste scenarios with the energy scenarios from 2010 to 2050 in Sweden. Total gross energy production from the waste is ranged from 38 to 186 TWh under an assumption of a balance between waste generation and treatment until 2050 but with a maximal energy output from the waste. The waste-to-energy can satisfy 6% to 47% of total energy supply in 2050, where the shares in the demands of motor fuels, power and heat can rise from 2%, 4% and 13% in 2010 to 61%, 30% and 133% under different waste-to-energy scenarios if a ten percentage of conversion and distribution loss is assumed. Considering the biofuels use with low waste intensity, the combination of "Biofuels 2050" with "Global sustainability" to form waste-to-energy scenarios should be prioritized over the others. Furthermore, the waste-to-energy can finally help mitigate CO_2 emission by 1 to 12 Mt in 2050, compared to base year 2010.

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