POTENTIAL FOR BIOMETHANE PRODUCTION WITH CARBON DIOXIDE CAPTURE AND STORAGE

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This report describes research sponsored by IEAGHG. This report was prepared by:

ECOFYS

The principal researchers were:

- J. Koornneef
- P. van Breevoort
- P. Noothout
- C. Hendriks
- L. Luning

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The expert reviewers for this report were:

- Jonas Helseth, Bellona
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- Phil Hare, Poyry
- Arthur Wellinger, Technical Coordinator IEA Bioenergy;
- David Baxter / Alessandro Agostini; JRC Petten, Task Leader Biogas IEA Bioenergy
- James Dooley, PNNL

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Further information or copies of the report can be obtained by contacting IEAGHG at:

IEAGHG, Orchard Business Centre,
Stoke Orchard, Cheltenham,
GLOS., GL52 7RZ, UK
Tel: +44(0) 1242 680753 Fax: +44 (0)1242 680758
E-mail: mail@ieaghg.org Internet: www.ieaghg.org

POTENTIAL FOR BIOMETHANE PRODUCTION AND CARBON DIOXIDE CAPTURE AND STORAGE

Key Messages

- Biomethane production in combination with carbon capture and storage (CCS) has the technical potential to remove up to 3.5 Gt of greenhouse gas emissions from the atmosphere in 2050. This is in the context of the required emissions reductions from the energy sector of over 30 Gt by 2050 (IEA CCS Roadmap 2013). Annual greenhouse gas emission savings could be almost 8 Gt in 2050 if natural gas is replaced by biomethane production with CCS.

- The maximum technical potential is provided by large scale gasification based production of biomethane with CCS which could have potential in regions where large scale infrastructure is already in place for the transport of biomass, natural gas and CO_2. Small scale biomethane production with CCS based on digestion, suitable for biomass with high water content, is most likely restricted to niche market applications. The technical potentials are limited by the availability of sustainable biomass.

- The economic potential depends strongly on the CO_2 price and natural gas price, and is much lower than the technical potential for all scenarios, the highest potential being 0.4Gt by 2050.

- Overall, the potential is most likely restricted to those regions that have favourable (high) natural gas and CO_2 prices and favourable infrastructure.

Background to the Study

In 2011, the IEAGHG R&D Programme published a report on the global potential of six technology routes that combine biomass with carbon capture and storage (CCS) titled: Potential for Biomass and Carbon Dioxide Capture and Storage (IEAGHG 2011/06). The study considered four electricity production routes and two routes for biodiesel and bio-ethanol production. This study addresses two additional technology routes combining the production of biomethane with the capture and storage of the co-produced carbon dioxide.

Scope of Work

The aim of this study is to provide an understanding and assessment of the global potential - up to 2050 - for BE-CCS technologies producing biomethane. It makes a distinction between: *Technical potential* (the potential that is technically feasible and not restricted by economical limitations) and the *Economic potential* (the potential at competitive cost compared to the reference natural gas, including a CO_2 price).

The study assesses two concepts to convert biomass into biomethane: gasification (followed by methanation) and anaerobic digestion (followed by gas upgrading). The types of feedstock taken into account are energy crops, agricultural residues and forestry residues. For digestion it also considers biogenic municipal solid waste, and animal manure and sewage sludge as feedstock.

Findings of the Study

Table 1, Figure 1 and Figure 2 summarise the most eminent results of this assessment. The results show the maximum technical potential in 2050 is found for the gasification route with CCS. In this route 79 EJ of biomethane is produced, leading to the removal of 3.5 Gt of CO_2 from the atmosphere. This is a significant potential when compared to the current (2009) global natural gas production of almost 106 EJ. On top of that, the substitution of 79 EJ of natural gas with biomethane would result in an additional greenhouse gas emission reduction of 4.4 Gt of CO_2 equivalents. In total, almost 8 Gt CO_2 eq. can be reduced through this route[1] and with it provides a significant reduction potential compared to the global energy-related CO_2 emissions, which grew to 30.6 Gt in 2010 (IEA 2011).

Table 1 Overview of global technical and economic potential per BE-CCS route for the view years 2030 and 2050

Technology route	Year	Technical potential				Economic potential	
		Primary energy	Final energy	CO_2 stored	GHG balance (CO_2 eq)	Final energy	GHG balance (CO_2 eq)
			EJ/yr	Gt/yr	Gt/yr	EJ/yr	Gt/yr
Gasification	2030	73.1	44.8	2.4	-1.8	2.7	-0.1
Gasification	2050	125.6	79.1	4.3	-3.5	4.8	-0.2
*Anaerobic digestion – EC and AR**	*2030*	*43.3*	*26.0*	*1.2*	*-1.1*	*1.4*	*-0.1*
*Anaerobic digestion – EC and AR**	*2050*	*74.7*	*44.8*	*2.1*	*-2.1*	*2.4*	*-0.1*
Anaerobic digestion – MSW	*2030*	*5.1*	*3.1*	*0.1*	*-0.1*	*3.1*	*-0.1*
Anaerobic digestion – MSW	*2050*	*10.6*	*6.4*	*0.3*	*-0.3*	*6.4*	*-0.3*
Anaerobic digestion - Sewage/ Manure	*2030*	*7.4*	*3.0*	*0.2*	*-0.2*	*3.0*	*-0.2*
Anaerobic digestion - Sewage/ Manure	*2050*	*13.8*	*5.5*	*0.4*	*-0.4*	*5.5*	*-0.4*
Anaerobic digestion – Total	2030	55.9	32	1.5	-1.4	7.4	-0.4
Anaerobic digestion – Total	2050	99.1	56.7	2.8	-2.7	14.3	-0.8

*Energy Crops and Agricultural Residues

The total technical potential for the digestion based route with CCS (digestion-CCS) is lower, 57 EJ, as a smaller fraction of the biomass potential for energy crops and residues (forestry and agriculture) can be used in this technology route as the technology is less suitable for the conversion of lignocellulosic biomass. The potential

[1] Note that 1 Gt of negative emissions is not the same as 1 Gt of emission reductions. Generally speaking, the emission reduction potential of BE-CCS options is equal to the amount of negative emissions plus the emissions of the technology or fuel it replaces, in this case natural gas. Throughout the remainder of the report it indicates negative emissions, not avoided or reduced emissions, unless otherwise indicated.

of the more suitable feedstock for digestion, being municipal solid waste (MSW), animal manure and sewage sludge, is relatively small. The potential of these sources sums up to almost 12 EJ (0.7 Gt CO_2eq) of biomethane in the year 2050.

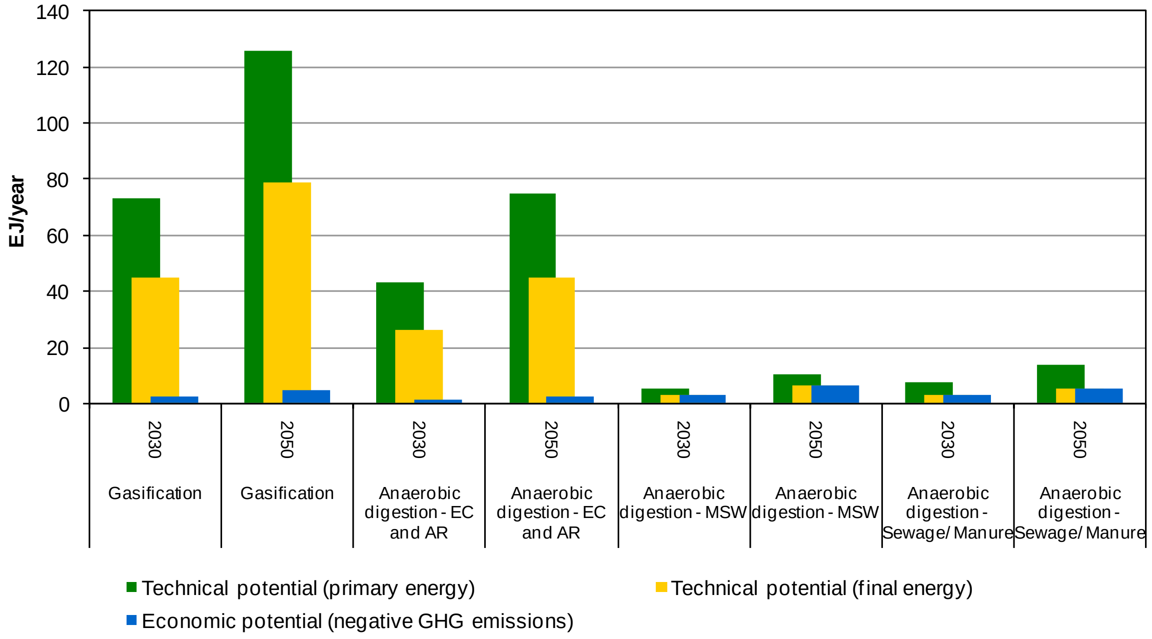

Figure 1 Global technical and economic energy potential (in EJ/yr) per BE-CCS route for the view years 2030 and 2050. Note that potentials are assessed on a route by route basis and cannot simply be added, as they may compete and substitute each other.

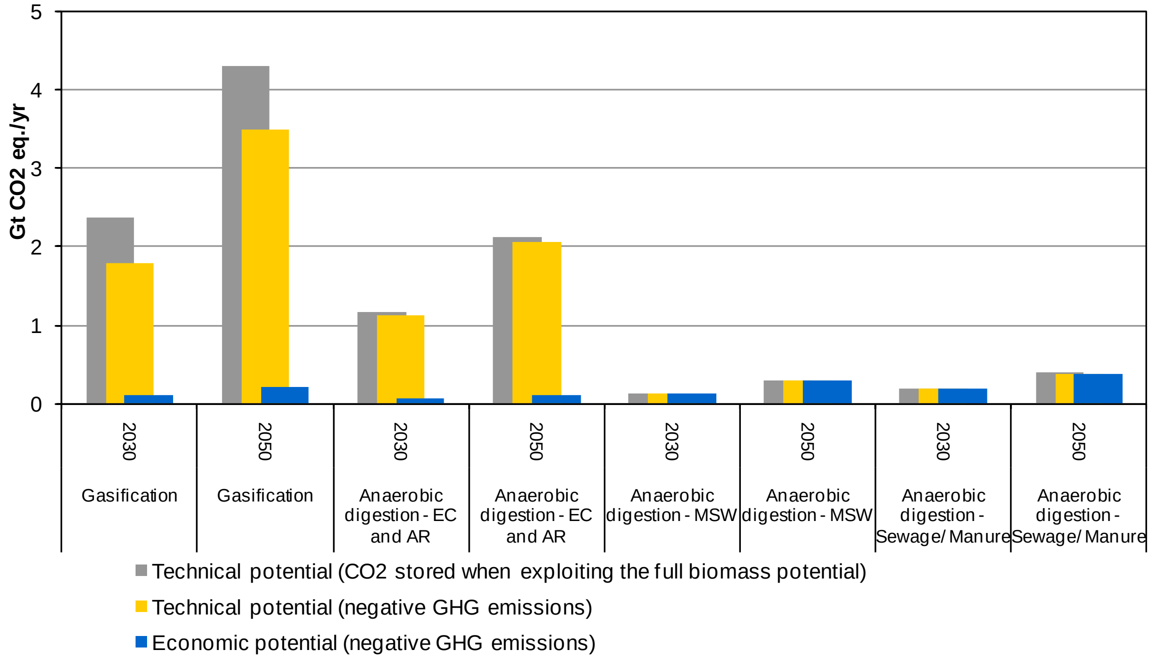

Figure 2 Greenhouse gas emission balance (in Gt CO_2 eq/yr) for the global technical and economic potential per BE-CCS route for the view years 2030 and 2050. Note that potentials are assessed on a route by route basis and cannot simply be added, as the biomass resources may compete with each other.

One of the interesting features of biomethane production for grid injection is that the separation of CO_2 is already an intrinsic step in the production process. This means that the incremental costs of adding CCS is potentially low.

The economic potential for biomethane-CCS is dominated by the CO_2 price and the natural gas price, which may vary per location. For almost all combinations of feedstock (energy crops, agricultural residues and forestry residues) and conversion technology there is only an economic potential at high natural gas prices (>11 €/GJ) combined with CO_2 prices of at least 20 €/tonne. An exception is the use of municipal solid waste (MSW) and sewage sludge in combination with anaerobic digestion which show already an economic potential at a CO_2 price of 20 €/tonne CO_2 and natural gas price of 6.7 €/GJ. The economic potential is the highest for digestion-CCS of animal manure/sewage sludge and MSW. When assuming a CO_2 price of 50 €/tonne, the economic potentials in 2050 reach 5.5 EJ (-0.4 Gt CO_2 eq) for animal manure/sewage sludge and 6.4 EJ (-0.3 Gt CO_2 eq) for MSW. Drivers for the deployment of biomethane are (EU) targets for biofuels, increasing security of supply (e.g. by reducing the import dependency of natural gas), and the presence of existing natural gas transport and distribution infrastructure.

Barriers typical for the deployment of digestion-CCS are high biomass transport costs which limit the plant size and it is likely that the small size of digesters also results in a high cost for connecting to the CO_2 and natural gas infrastructure. Nevertheless, anaerobic digestion-CCS of MSW, sewage sludge and animal manure might become a promising niche application that offers the opportunity to process waste, reduce carbon emissions and produce valuable biomethane. Further it is important for the digestion-CCS route to look for possible valuable end-use of captured CO_2 to enhance business case for smaller systems with CO_2 capture (e.g. CO_2 use in industry and in horticulture).

The gasification-CCS route fits best with a large scale infrastructure for the transport of biomass, natural gas and CO_2; that is, a more centralised production of biomethane combined with CCS. The implementation of decentralised production of biomethane and end-use, in combination with CCS is deemed unlikely, due to infrastructural requirements for both CO_2 and natural gas.

Expert reviewer's comments

Comments were received from five reviewers. Overall, the reviewers thought that with the revisions, the report would be a good contribution to the subject.

The majority of the negative comments stemmed from the need to have read the original report IEAGHG 2011/06 for the methodology and assumptions, and these peer reviewers were different to those used on that report (only one being the same). This follow up report on biomethane refers to the original report for assumptions and detailed explanation of methods. It was therefore recommended that the report's conciseness was improved to enable this report to be seen as an addendum of the original report. Though more concise, further explanation in some areas of the report was necessary, such as sustainability criteria used and when stressing the major findings by putting them in context to the approach used, uncertainty and why this is important.

The terminology in the draft report appeared a little inconsistent, and needed to be revised, and a little more discussion/explanation was needed when discussing terms to assist readability. There were various technical aspects which needed addressing also. There are some assumptions and discussion points which would be useful to address, such as avoided methane emissions versus GHG savings, the sustainability criteria, CO_2 price allocation producer versus end user and branched or centralised grids; and discussion points which could be easily removed as they add little to the report.

The reviewer's comments were then addressed by the contractors in a revised final report.

Conclusions

- Biomethane production in combination with carbon capture and storage has the technical potential to remove up to 3.5 Gt of greenhouse gas emissions from the atmosphere in 2050
- Annual greenhouse gas emission savings could be almost 8 Gt in 2050 if natural gas is replaced by biomethane production with CCS.
- The economic potential depends strongly on the CO_2 price and natural gas price.
- Large scale gasification based production of biomethane with CCS could have potential in regions where large scale infrastructure is already in place for the transport of biomass, natural gas and CO_2.
- Small scale biomethane production with CCS based on digestion is most likely restricted to niche market applications.

Overall, it is concluded that the economic potential for biomethane combined with CCS is most likely restricted to those regions that have favourable (high) natural gas and CO_2 prices, and have favourable infrastructural conditions. A logical next step in understanding the potential of technology routes that combine biomethane production with CCS would be to assess more location specific (region, country, local area) conditions. The combination of elements like presence of suitable industry, infrastructure and biomass import facilities, and technical knowledge may provide synergies for economical production of biomethane combined with CO_2 removal and re-use or storage. A focus could be on regions with demand for CO_2 (industry, horticulture) or starting CCS infrastructure, (dense) natural gas infrastructure, high (local) availability of biomass and/or high natural gas import.

Potential for Biomethane production with Carbon Dioxide Capture and Storage

Ecofys Netherlands BV
P.O. Box 8408
NL- 3503 RK Utrecht
Kanaalweg 16-A
NL- 3526 KL Utrecht
The Netherlands

W: www.ecofys.com
T: +31 (0) 30 66 23 300
F: +31 (0) 30 66 23 301
E: info@ecofys.com

Potential for Biomethane production with Carbon Dioxide Capture and Storage

By: Joris Koornneef (j.koornneef@ecofys.com),
Pieter van Breevoort (p.vanbreevoort@ecofys.com)
Paul Noothout (p.noothout@ecofys.com)
Chris Hendriks (c.hendriks@ecofys.com)
Luchien Luning (l.luning@ecofys.com)

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by order of:
IEA Greenhouse Gas R&D Programme

Foreword

The IEA GHG R&D programme has commissioned Ecofys to explore the global potential of combining biomass and carbon capture and storage (BE-CCS). This has resulted in the IEA GHG report: 'Potential for Biomass and Carbon Dioxide Capture and Storage' (2011/06), comprising six main technology routes. Based on the results, the ExCo members of the IEA GHG R&D programme advised to expand the report with two additional routes. These technology routes should focus on biomethane production in combination with CO_2 capture, transport and storage to replace 'conventional' natural gas.

The technology routes addressed in this report are anaerobic digestion and gasification of biomass in combination with methanation. The digestion route produces biogas, which is upgraded to biomethane by removing CO_2 and other impurities. Via gasification Synthetic Natural Gas (SNG) is produced, or in this case bioSNG. Throughout this report, we will use the term 'biomethane' for both bioSNG as the upgraded biogas.

The analysis of both technology routes is done using the same methodology as applied for the six technologies evaluated in the main report 'Potential for Biomass and Carbon dioxide Capture and Storage'. Details of the methodology are not provided in this report and the reader is referred to the main report for detailed description on the methodology applied and for the general assumptions. Textboxes are provided in cases the analysis of the two routes deviates from the original methodology (see section 2.2 and 3.2).

The scope of this report is limited to the technical and economic potential. The realisable potential - that has been part of the first report on BE-CCS technologies producing electricity and biofuels - has been excluded from the analysis in this report.

Glossary

BE-CCS – Bio-energy conversion combined with Carbon Capture and Storage

Biogas – Gas produced from the anaerobic digestion of biogenic feedstock. The gas contains mainly methane and carbon dioxide.

Biomethane – Gas produced by upgrading biogas or by Synthetic Natural Gas production. Contains mainly methane and the quality is sufficient to inject into a natural gas grid.

BioSNG – Synthetic Natural Gas (SNG) produced through biomass gasification followed by the methanation and purification. Contains mainly methane and the quality is sufficient to inject into a natural gas grid.

CCS - Carbon Capture and Storage

Product gas – Gas produced through biomass gasification at *moderate* temperature levels. Product gas consists mainly of hydrogen, carbon monoxide, methane, C_xH_y and impurities (e.g. tar).

Syngas - Synthesis gas produced through biomass gasification at *high* temperature levels. Syngas consists mainly of hydrogen and carbon monoxide.

Executive summary

Note on units
1 EJ (exaJoule) = 10^{18} Joule; 1 EJ ~ 24 Mtoe
1 Gt (Gigatonne) = 10^9 tonne = 10^{15} gram

In 2011, the IEA GHG R&D programme published a report on the global potential of six technology routes that combine biomass with carbon capture and storage (CCS) titled: Potential for Biomass and Carbon Dioxide Capture and Storage (2011/06)(IEA GHG 2011). The study considered four electricity production routes and two routes for biodiesel and bio-ethanol production. In this report we address two additional technology routes combining the production of biomethane with the capture and storage of the co-produced carbon dioxide.

The aim of this study is to provide an understanding and assessment of the global potential - up to 2050 - for BE-CCS technologies producing biomethane. We make a distinction between: *Technical potential* (the potential that is technically feasible and not restricted by economical limitations) and the *Economic potential* (the potential at competitive cost compared to the reference natural gas, including a CO_2 price).

We assess two concepts to convert biomass into biomethane: gasification (followed by methanation) and anaerobic digestion (followed by gas upgrading). The types of feedstock we take into account are energy crops, agricultural residues and forestry residues. For digestion we also consider biogenic municipal solid waste, and animal manure and sewage sludge as feedstock.

Table 1, Figure 1 and Figure 2 summarise the most eminent results of this assessment. The results show the maximum technical potential in 2050 is found for the gasification route with CCS. In this route 79 EJ of biomethane is produced, leading to the removal of 3.5 Gt of CO_2 from the atmosphere. This is a significant potential when compared to the current (2009) global natural gas production of almost 106 EJ. On top of that, the substitution of 79 EJ of natural gas with biomethane would result in an additional greenhouse gas emission reduction of 4.4 Gt of CO_2 equivalents. In total, almost 8 Gt CO_2 eq can be reduced through this route[1] and with it provides a

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significant reduction potential compared to the global energy-related CO_2 emissions which grew to 30.6 Gt in 2010 (IEA 2011).

The total technical potential for the digestion based route with CCS (digestion-CCS) is lower, 57 EJ, as a smaller fraction of the biomass potential for energy crops and residues (forestry and agriculture) can be used in this technology route as the technology is less suitable for the conversion of lignocellulosic biomass. The potential of the more suitable feedstock for digestion, being municipal solid waste (MSW), animal manure and sewage sludge, is relatively small. The potential of these sources sums up to almost 12 EJ (0.7 Gt CO_2eq) of biomethane in the year 2050.

Table 1 Overview of global technical and economic potential per BE-CCS route for the view years 2030 and 2050

Technology route	**Year**	**Technical potential**				**Economic potential**	
		Primary energy	Final energy	CO_2 stored	GHG balance (CO_2 eq)	Final energy	GHG balance (CO_2 eq)
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Anaerobic digestion - Total	2030	55.9	32	1.5	-1.4	7.4	-0.4
Anaerobic digestion - Total	2050	99.1	56.7	2.8	-2.7	14.3	-0.8

*Energy Crops and Agricultural Residues

One of the interesting features of biomethane production for grid injection is that the separation of CO_2 is already an intrinsic step in the production process. This means that the incremental costs of adding CCS is potentially low.

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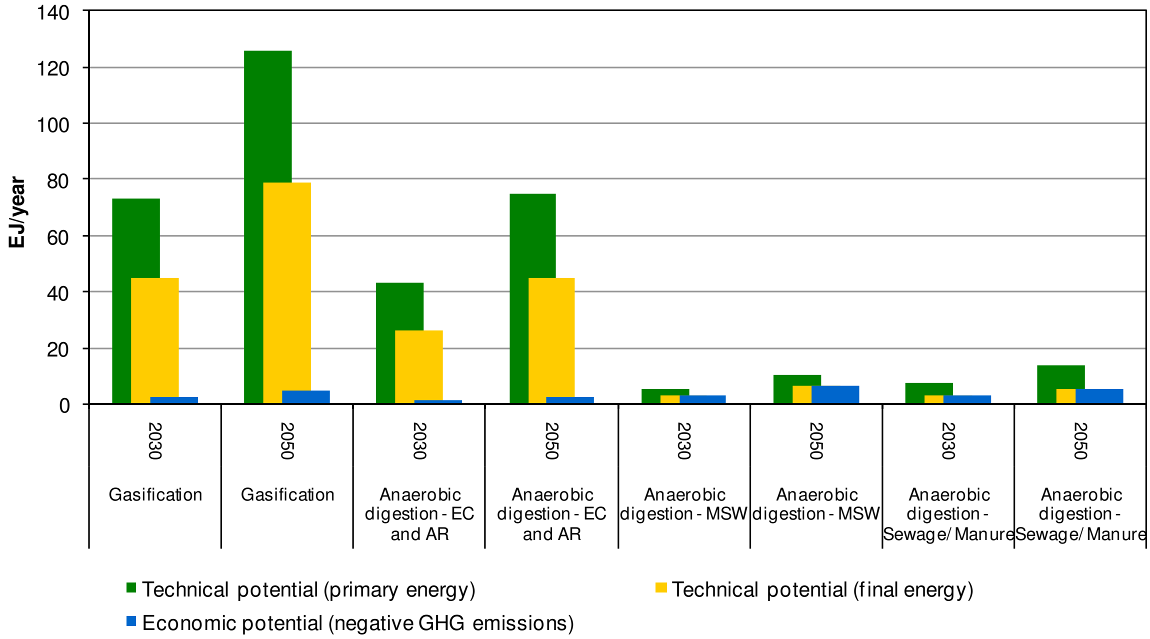

Figure 1 Global technical and economic energy potential (in EJ/yr) per BE-CCS route for the view years 2030 and 2050. Note that potentials are assessed on a route by route basis and cannot simply be added, as they may compete and substitute each other.

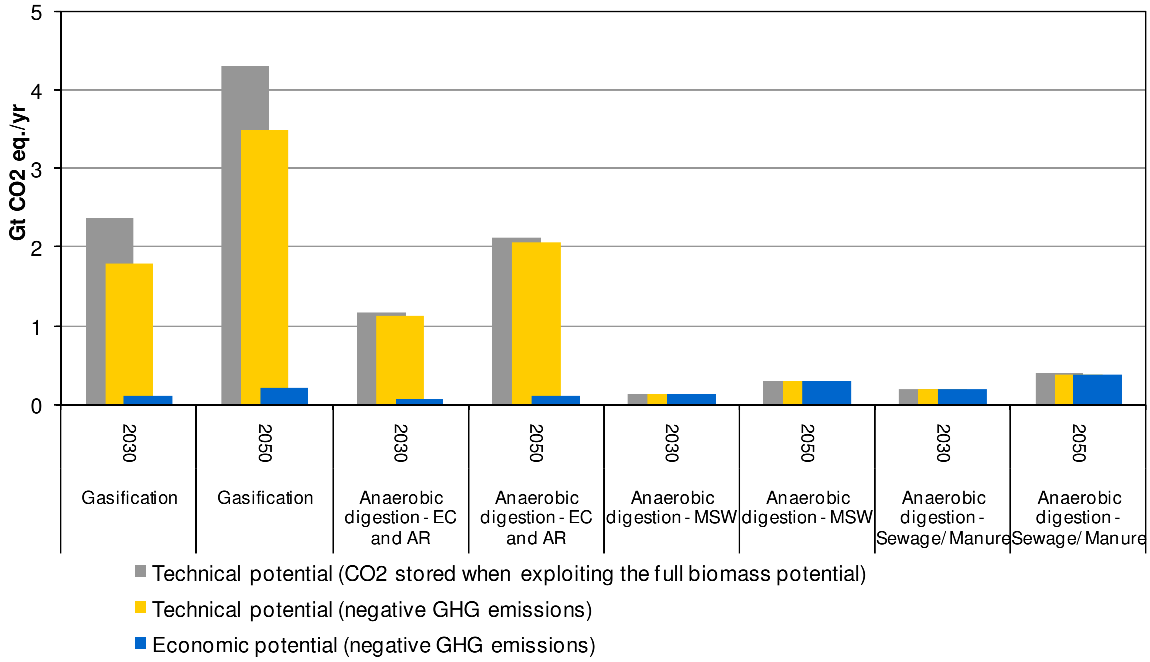

Figure 2 Greenhouse gas emission balance (in Gt CO_2 eq/yr) for the global technical and economic potential per BE-CCS route for the view years 2030 and 2050. Note that potentials are assessed on a route by route basis and cannot simply be added, as the biomass resources may compete with each other.

The economic potential for biomethane-CCS is dominated by the CO_2 price and the natural gas price, which may vary per location. For almost all combinations of feedstock (energy crops, agricultural residues and forestry residues) and conversion technology there is only an economic potential at high natural gas prices (>11 €/GJ) combined with CO_2 prices of at least 20 €/tonne. An exception is the use of municipal solid waste (MSW) and sewage sludge in combination with anaerobic digestion which show already an economic potential at a CO_2 price of 20 €/tonne CO_2 and natural gas price of 6.7 €/GJ. The economic potential is the highest for digestion-CCS of animal manure/sewage sludge and MSW. When assuming a CO_2 price of 50 €/tonne, the economic potentials in 2050 reach 5.5 EJ (-0.4 Gt CO_2 eq) for animal manure/sewage sludge and 6.4 EJ (-0.3 Gt CO_2 eq) for MSW. Drivers for the deployment of biomethane are (EU) targets for biofuels, increasing security of supply (e.g. by reducing the import dependency of natural gas), and the presence of existing natural gas transport and distribution infrastructure.

Barriers typical for the deployment of digestion-CCS are high biomass transport costs which limit the plant size. The small size of digesters most likely also results in high cost for connecting to the CO_2 and natural gas infrastructure. Nevertheless, anaerobic digestion-CCS of MSW, sewage sludge and animal manure might become a promising niche application that offer the opportunity to process waste, reduce carbon emissions and produce valuable biomethane. Further it is important for the digestion-CCS route to look for possible valuable end-use of captured CO_2 to enhance business case for smaller systems with CO_2 capture (e.g. CO_2 use in industry and in the horticulture).

The gasification-CCS route fits best with a large scale infrastructure for the transport of biomass, natural gas and CO_2; that is, a more centralised production of biomethane combined with CCS. The implementation of decentralised production of biomethane and end-use, in combination with CCS is deemed unlikely, due to infrastructural requirements for both CO_2 and natural gas.

Overall, we conclude that the economic potential for biomethane combined with CCS is most likely restricted to those regions that have favourable (high) natural gas and CO_2 prices, and have favourable infrastructural conditions. A logical next step in understanding the potential of technology routes that combine biomethane production with CCS is to assess more location specific (region, country, local area) conditions. The combination of elements like presence of suitable industry, infrastructure and biomass import facilities, and technical knowledge may provide synergies for economical production of biomethane combined with CO_2 removal and re-use or storage. A focus could be on regions with demand for CO_2 (industry, horticulture) or starting CCS infrastructure, (dense) natural gas infrastructure, high (local) availability of biomass and/or high natural gas import.

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Table of contents

1 Introduction

IEA GHG has recently published a study on the global potential for biomass with Carbon Capture and Storage (BE-CCS) that covers a selection of biomass combustion technologies and two biofuel options (bio-ethanol and Fischer-Tropsch diesel from biomass) combined with CCS. In that study, those BE-CCS technology routes were selected that 'have the greatest anticipated potential'. Based on expert reviews other potentially interesting BE-CCS routes are identified that are worthwhile investigating further. One of those routes is biomethane production in combination with CCS, or biomethane-CCS.

Biomethane can be produced through several routes. Gasification combined with methanation, and upgraded biogas produced by anaerobic digestion seems to be promising technologies that can be combined with CO_2 capture. Biomethane can be produced to meet current natural gas specifications by upgrading the biogas. In both routes, a final step to meeting specifications is the removal of CO_2 which is then available for geological storage. The produced biomethane can be transported using the existing natural gas infrastructure.

The aim of this study is to provide an understanding and assessment of the global technical and economic potential for the combination of biomethane production with carbon capture and storage up to 2050.

More details on the methodologies used to define the potentials are provided in (IEA GHG 2011) and the chapters on the technical potential (chapter 2) and economic potential (chapter 3).

Next to the quantitative estimates of these potentials, also in the form of regional and global supply curves, this study identifies barriers to the deployment of biomethane production combined with CCS (chapter 4). We also present recommendations to solve possible obstacles and enhance drivers to stimulate the deployment of biomethane-CCS technologies.

A sensitivity analysis (chapter 5) is followed by a detailed discussion of the results and limitations of this study (chapter 6) to provide insights into the certainty of the results. Conclusions and recommendations are provided in chapter 7. An overview of the general assumptions is provided in Appendix A. Appendix B presents details on the determination of the biomass potential. A detailed overview of results can be found in Appendix C.

2 Technical potential

In this chapter, we discuss two biomethane production routes combined with CCS: anaerobic digestion and gasification followed by methanation. Before estimating the technical potential, we first discuss the status, specifications and technical performance the routes in the view years, 2030 and 2050. The technical potential is expressed as the primary and final energy potential and in terms of net greenhouse gas emissions. Appendix B presents details on the biomass potential. Detailed results are presented in Appendix C.

2.1 Summary

Table 2 - 1, Figure 2 - 1 and Figure 2 - 2 provide an overview of the estimated technical potentials. A detailed overview of results can be found in Appendix C.

The availability of biomass differs between the gasification and digestion routes, mainly because of two reasons. Firstly, the digestion route is typically more suitable for feedstock with high moisture content and is less suitable for the conversion of lignocellulosic biomass. Therefore a part of the biomass potential for energy crops and residues is excluded. Secondly, municipal solid waste, animal manure and sewage sludge are suitable feedstock for the digestion route, but less suitable for the gasification route. Taking these considerations into account, the primary energy potential for digestion in 2050 amounts to 99 EJ and the potential for the gasification route sums up to 126 EJ.

In all regions there is sufficient CO_2 storage capacity available to store the captured CO_2 from each biomethane production route (see Figure 2 - 1). Compared to power production routes from biomass (analysed in (IEA GHG 2011)), in the biomethane routes a relatively small fraction of the carbon in the original feedstock is captured and stored. This is assumed to range between 27% and 38%. Therefore a relatively small storage capacity is required when converting the full biomass potential.

How much CO_2 potentially needs to be stored depends on the primary energy potential and the fraction of carbon in the feedstock that can be removed in the form of CO_2. This amount increases towards 2050, mainly because of an expected increase in the sustainable biomass potential. The amount of negative greenhouse gas emissions is highest for gasification-CCS: 3.5 Gt in 2050. For digestion-CCS the maximum amount of negative emissions is estimated at 2.8 Gt CO_2 eq in 2050.[2]

The technical potential expressed in final energy is mainly determined by the primary energy availability and the conversion efficiency. The latter is assumed to be higher for the gasification route than for the digestion route. In 2050, the technical potential (expressed in final energy) for gasification route is 79 EJ, and 57 EJ for the anaerobic digestion route.

Table 2 - 1 Overview of technical potentials per conversion routes

Route	Year	Technical potential			
		Primary energy EJ/y	Final energy EJ/y	CO_2 stored Gt/y	net GHG emissions Gt/y
Gasification	2030	73.1	44.8	2.4	-1.8
Gasification	2050	125.6	79.1	4.3	-3.5
Anaerobic digestion - EC and AR*	*2030*	*43.3*	*26.0*	*1.2*	*-1.1*
Anaerobic digestion - EC and AR*	*2050*	*74.7*	*44.8*	*2.1*	*-2.1*
Anaerobic digestion - MSW	*2030*	*5.1*	*3.1*	*0.1*	*-0.1*
Anaerobic digestion - MSW	*2050*	*10.6*	*6.4*	*0.3*	*-0.3*
Anaerobic digestion - Sewage/ Manure	*2030*	*7.4*	*3.0*	*0.2*	*-0.2*
Anaerobic digestion - Sewage/ Manure	*2050*	*13.8*	*5.5*	*0.4*	*-0.4*
Anaerobic digestion – total	2030	55.9	32	1.5	-1.4
Anaerobic digestion – total	2050	99.1	56.7	2.8	-2.7

*Energy Crops and Agricultural Residues

[2] The amount of negative emissions might differ from the amount of CO_2 stored, because indirect emissions (e.g. from electricity production or biomass transport) are taken into account as well when we analyse the GHG balance. Therefore, we distinguish GHG balance and the amount of CO_2 stored.

It should be highlighted that 1 Gt of negative emissions is not the same as 1 Gt of emission reductions. Emission reductions always depend on a reference situation or scenario. This is best explained with the use of an example. When combusting 1 GJ of natural gas 56 kg of CO_2 is emitted. BE-CCS technologies may deliver negative emissions by storing CO_2 originating from biomass. In the table above the negative emissions per GJ of biomethane range between 40 and 69 kg/GJ. Thus when replacing one GJ of natural gas by biomethane with CCS then at least the 56 kg of CO_2 is avoided plus the amount of negative emissions achieved by implementing BE-CCS. Generally speaking, the emission reduction potential of BE-CCS options is equal to the amount of negative emissions plus the emissions of the technology or fuel it replaces. A technical potential of 1 Gt is thus at least equal to 1 Gt of emission reduction, but the exact amount depends on the technologies being replaced by BE-CCS technologies.

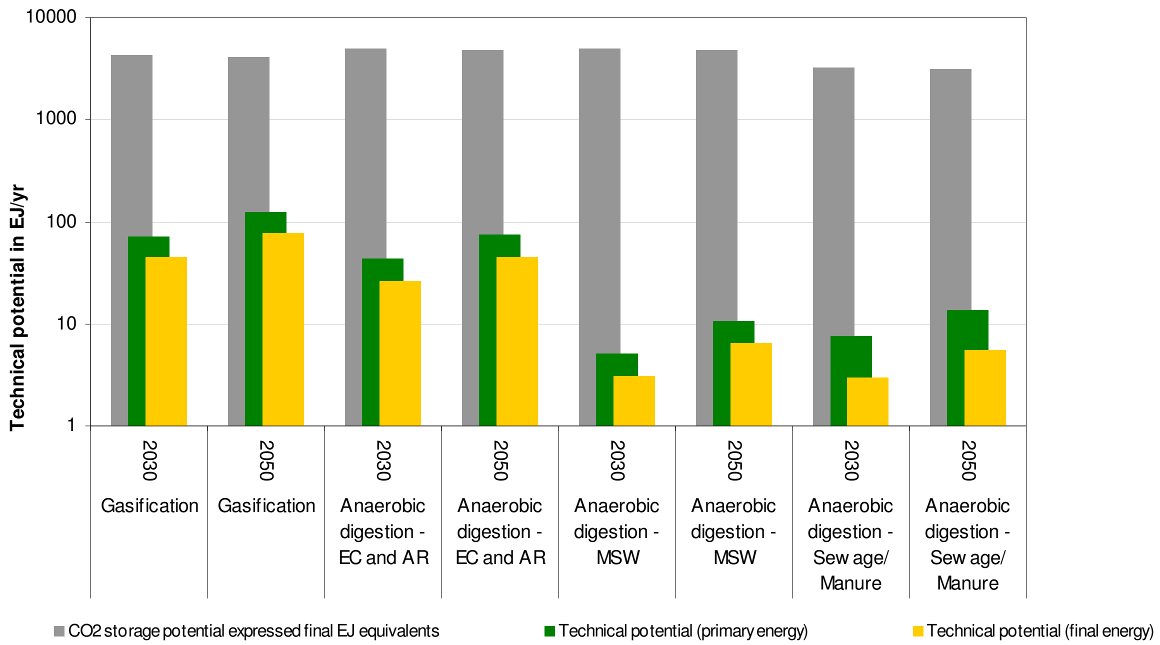


Figure 2 - 1 Technical potential for the two BE-CCS routes showing the primary biomass potential, final energy potential and the CO_2 storage potential expressed in final energy equivalents per route taking into account the carbon removal efficiency per technology route. Note the logarithmic scale.

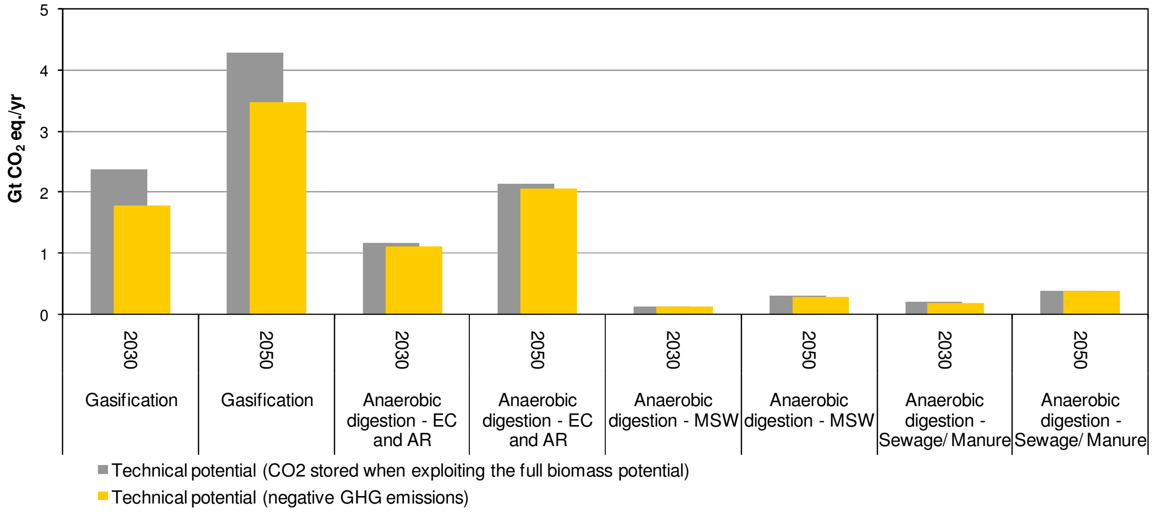


Figure 2 - 2 Amount of CO_2 stored and the technical potential expressed in net negative greenhouse gas emissions. For each route, we assume exploiting the full biomass potential.

2.2 Determining the technical potential

The technical potential is determined either by restriction in biomass supply or by limitations in CO_2 storage potential.

In IEA GHG (2011) electricity production with CCS and biofuel production with CCS was assessed using three categories of biomass feedstock: energy crops, agricultural residues and forestry residues. For the production of biomethane by bio-gasification the same feedstock potential is assumed. We refer to IEA GHG (2011) for details on the potential estimations for these types of feedstock.

For the digestion-CCS additional type of feedstock are taken into account route, being: municipal solid waste and manure & sewage sludge. The technology is however not considered to be suitable to convert the (full) potential for forestry residues and energy crops. Between the biomethane production technology routes there are thus differences in the potential biomass that is suitable for conversion. This has considerable effects on the technical potential for both routes (see section 2.4 for details).

To determine the technical potential for the biomethane technologies per region, we combine existing studies on regional biomass potentials (in EJ/yr primary energy) and regional CO_2 storage potentials (in Gt CO_2). The net energy conversion efficiency (including the energy use for CCS) and the carbon removal efficiency of the BE-CCS route then determine the technical potential for biomass CCS in terms of primary energy, final energy and net (negative) GHG emissions [2,3]. In this study, we distinguish seven regions:

- Africa & Middle East (AFME)
- Asia (ASIA)
- Oceania (OCEA)
- Latin America (LAAM)
- Non-OECD Europe & the Former Soviet Union (NOEU)
- North America (NOAM)
- OECD Europe (OEU)

We first calculate the *global* potential, determined by the global storage and biomass potential assuming that there are no restrictions on interregional transport of biomass and CO_2. In a second step, we exclude interregional transport of biomass.[4] In that case the BE-CCS potential may be lower as regional biomass availability or CO_2 storage capacity may pose a constraint on the implementation of BE-CCS technologies.

2.3 Specifications and assumptions in analysed BE-CCS routes

In Figure 2 - 3, we show the steps that are analysed in detail to estimate the technical potential. In the sections below we discuss the technical performance of these steps and the assumptions that were made.

[3] Throughout this report we will provide the results expressed in negative emissions, not avoided or reduced emissions, unless otherwise indicated.
[4] In the figures in section 2.4, 'World' and 'World2' indicate the potentials that include, respectively exclude interregional transport.

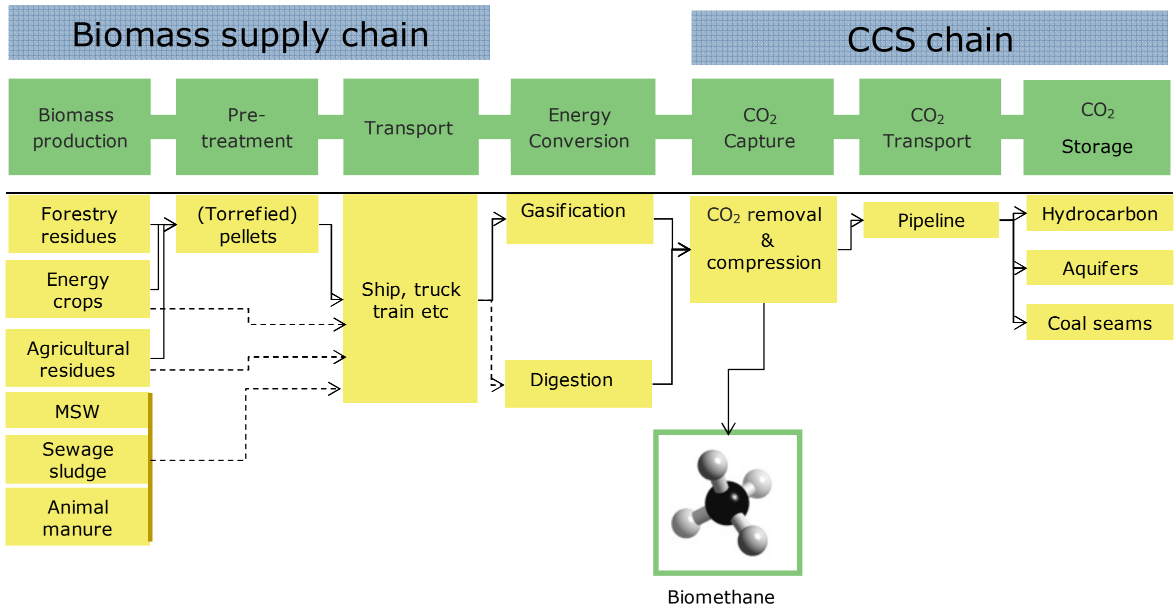


Figure 2 - 3 Chain elements in the BE-CCS routes (in green). Per chain element the assessed options are indicated (in yellow). Note that MSW, sewage sludge and animal manure are only applied in the digestion route (dashed lines) and do not require pre-treatment in the form of densification or torrefaction.

2.3.1 Sustainable biomass potential

Energy crops, forestry residues and agricultural residues are feedstock types that are appropriate for the gasification route, but not always for the digestion based route. [5] The digestion route is typically fed with wet feedstock. Examples of wet feedstock are animal manure and sewage sludge. Additionally, municipal solid waste (MSW) can be used as a feedstock for the digestion process. Lignin materials can not be degraded in

[5] In IEA GHG (2011) three categories of biomass are assessed: Energy crops, Forestry residues and Agricultural residues. See for more details Hoogwijk, M. (2004). On the global and regional potential of renewable energy sources. Science, Technology & Society. Utrecht, Utrecht University. **PhD:** 256, Florentinus, A., C. Hamelinck, et al. (2008). Worldwide potential of aquatic biomass. Utrecht, Ecofys, Bauen, A., G. Berndes, et al. (2009). Bioenergy – a Sustainable and Reliable Energy Source - A review of status and prospects
IEA bioenergy, ECN, E4tech, Chalmers University of Technology, Copernicus Institute of the University of Utrecht, van Vuuren, D. P., J. v. Vliet, et al. (2009). "Future bio-energy potential under various natural constraints." Energy Policy(37): 4220-4230 , Hoogwijk et al. (2010). Global potential of biomass for energy, in Global Energy Assessment -Preliminary results, More info: www.iiasa.ac.at/Research/ENE/GEA/index_gea.html , IIASA (forthcoming). Global Energy Assessment International Institute for Applied Systems Analysis .

the anaerobic digester.[6] Therefore, we exclude the so-called lignocellulosic biomass from the biomass potential for digestion. This implies that forestry residues are not included in the potential for digestion. Furthermore, we assume that 30% of the biomass from energy crops and agricultural residues is lignocellulosic and is consequently not applicable for this route. See chapter 6 "Discussion" for a discussion on this assumption.

For the digestion routes, we report on three categories of biomass feedstock:

- Energy crops and residues (excluding 30% lignocellulosic biomass and forestry residues)
- Municipal solid waste (MSW)
- Animal manure and sewage sludge

Table 2 - 2 Overview of the applied biomass types and their primary energy potentials per conversion route: gasification or digestion. Municipal Solid Waste (MSW) and Manure and sewage sludge have properties that match very well with anaerobic digestion and are therefore included. Because lignocellulosic biomass degrades very slowly in a digester, a smaller (compared to gasification) share of the energy crops and residues can be used in digesters: Forestry residues are excluded in this route and 30% of the energy crops and agricultural residues is assumed to be lignocellulosic. The estimates are based on work reported in IEA GHG (2011), by IIASA (forthcoming) and own estimates. See more detailed information in Appendix B.

Feedstock	Gasification		Digestion	
	Primary energy potential (EJ/y)			
	2030	**2050**	**2030**	**2050**
Energy crops	39	65	27	45
Agricultural residues	23	42	16	29
Forestry residues	11	19	Excluded	
Municipal solid waste	Excluded		5	11
Manure and sewage sludge			7	14
Total	**73**	**126**	**56**	**99**

16/93

[6] Most anaerobic organisms cannot degrade lignin (or woody) materials

2.3.2 Biomass pre-treatment and transport

Most forms of biomass tend to have a relatively low energy density per unit of volume or mass. Long distance transport and international trade is limited to commodities that have sufficient energy densities. Pre-treatment of biomass is therefore required to make transport economic and energetic viable. For the gasification based routes we assume torrefaction and densification.[7]

Digestion, on the other hand, is typically fed with wet biomass and pre-treatment in the form of drying and pelletizing is not recommendable. Nevertheless, depending on the type of biomass used for the digestion process other forms of pre-treatment are needed. For MSW, shredding and contaminant removal is needed and should be regarded as pre-treatment that is either performed at the MSW collection point or at the digestion plant site. The intensity of the separation and other pre-treatment activities are strongly related to the composition of the MSW, which differs strongly over the world. More on this topic can be found in the Discussion section in chapter 6. For manure and sewage there are no further pre-treatment steps required which are not already included in the on-site purification process, which is here assumed to be included within the 'conversion' step.

2.3.3 Technology description gasification based biomethane production

This section provides an overview of the current development status, scale and efficiency of the gasification technologies (see section 2.3.4. for an overview of the digestion technologies).

Technologies for the production of Synthetic Natural Gas (SNG) are in development since the 1970s, driven by high prices for oil and gas at that moment. This development has led to the construction of large-scale SNG-plants in the United States where lignite was gasified to produce syngas and subsequently SNG. Over the last decade, gasification plants for the production of SNG *based on biomass* have been developed in Austria, Switzerland, Germany, France, the Netherlands and Sweden (Van der Drift, Zwart et al. 2010).

In this study, two promising gasification technologies in combination with methanation are assessed as they are considered to be promising options for the future. These

[7] For more detailed information see IEA GHG (2011). Potential for Biomass and Carbon Dioxide Capture and Storage, IEA Greenhouse Gas R&D Programme (IEA GHG), Ecofys.

options are the Fast Internally Circulating Fluidised Bed (FICFB) gasification plant (one pilot plant, located in Güssing, Austria) and the MILENA plant (one pilot plant, operated by ECN). Both options have the advantage that the producer gas (gas produced by gasification of the biomass) has relative high methane content, high H_2/CO ratios and virtually no nitrogen dilution. These are favourable conditions for the subsequent methanation step. In this production step biomethane is produced that has sufficient quality to inject into a natural gas grid (E4Tech and NNFCC 2010).

Figure 2 - 4 and Figure 2 - 5 present the development status of biomass conversion technologies. The FICFB and the MILENA technologies are both gasification technologies in combination with methanation (see Figure 2 - 4) and are currently demonstrated.

FICFB gasification plant

The FICFB gasifier in Güssing is a gasification pilot plant to test several applications of syngas, among which are bio-SNG (Substitute Natural Gas), Fischer Tropsch (FT) (bio)diesel and Combined Heat & Power (CHP). The plant became operational in 2001 and is currently used as a CHP-plant. The exact capacity of the pilot depends on the use. The production capacity for biomethane is about 1 MW_{th} (Carbo, Smit et al. 2010). The overall energy efficiency from biomass to biomethane of the FICFB gasification plant is 64% (Van der Drift, Zwart et al. 2010).

For the future, there are plans to upscale the FICFB gasifier to 50 MW to supply both biomethane and heat (Van der Drift, Zwart et al. 2010). Involved expert do not expect technical limitations that would impede scaling up the technology, e.g. to 1000 MW, towards 2030 and 2050.

MILENA gasification plant

In 2004, ECN tested the MILENA technology on a lab scale using a 25kW gasifier. At the end of 2007 an 800 kW MILENA gasifier started operating (ECN 2008). Unlike the FICFB pilot plant, the MILENA was developed to readily produce syngas with a significant methane concentration, which would make it very suitable in bioSNG applications. The energy overall efficiency of the MILENA to convert biomass to SNG is about 68 - 70% (Meijden 2010; Van der Drift, Zwart et al. 2010).

The next step in the development of the MILENA concept will be a 12 MW demonstration plant, planned for 2015. From there the MILENA gasifier could be developed towards commercial-scale demonstration plant and finally to a full-scale commercial plant of 1 GW (ECN 2008). At that scale the MILENA gasifier might be combined with CO_2 capture, transport and storage (Carbo 2011).

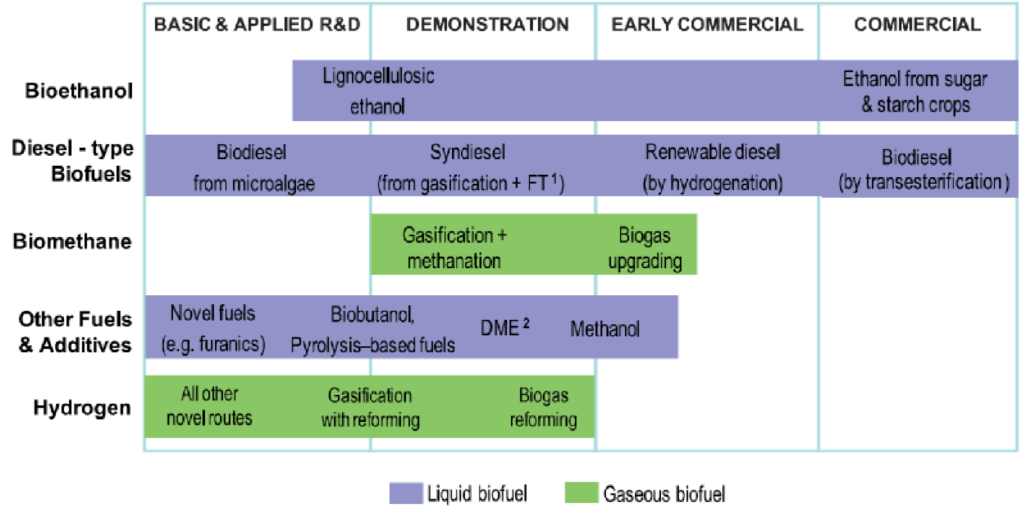


Figure 2 - 4 Development status of main conversion routes to produce (transport) fuels from biomass (source: (Bauen, Berndes et al. 2009)) (1 = Fisher Tropsch, 2= Dimethylether)

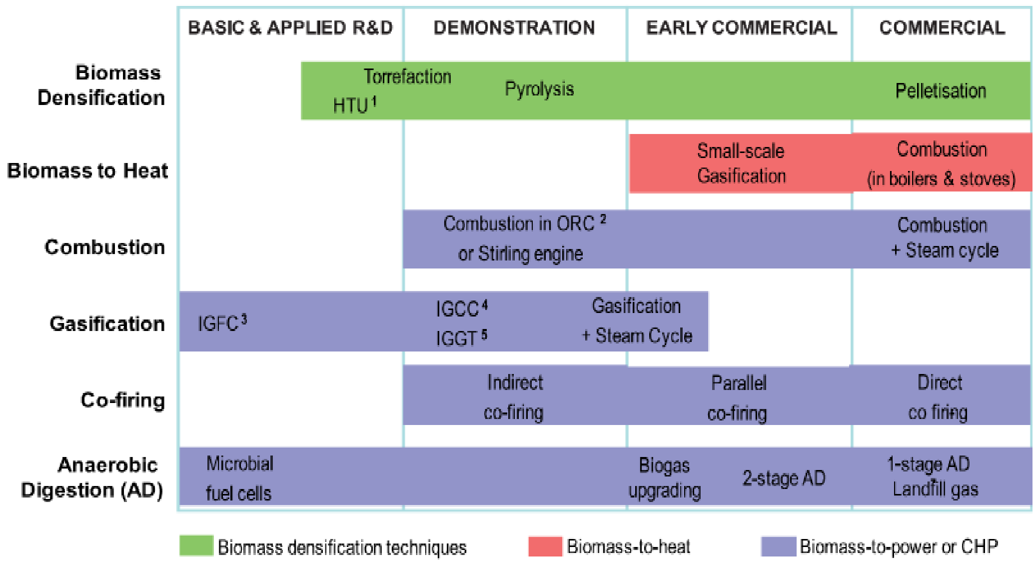


Figure 2 - 5 Development status of main biomass upgrade (densification) and conversion technologies (from: (Bauen, Berndes et al. 2009)) (1 = Hydrothermal upgrading, 2= Organic Rankine Cycle, 3 = Integrated gasification with fuel cell, 4 and 5 = Integrated Gasification with combined cycle/gas turbine)

2.3.4 Technology description for digestion based biomethane production

The digestion route is in certain configurations already a commercial technology and used as such. In Germany the number of digesters increased from 100 in 1990 to approximately 6,000 at the end of 2010 (IEA Bioenergy 2011). Biogas production through anaerobic digestion technology is considered a mature technology for the treatment of slurries and other feedstock with low (typically less than ~10%) dry matter content (Murphy and Power 2009), but can also be used for feedstock with higher dry matter content. It is not suitable for feedstock with high lignin content, i.e. woody biomass.

The capacity of a tank is limited to the ability to “stir” or “mix” the biomass properly to stimulate the digestion process. This also depends on the medium used in the digesters. One facility can consist of several digesters tanks. As transportation of wet biomass is expensive, most digesters facilities are located near the biomass source. This limits the capacity of the digesters considerably, which vary typically between 10 and 15 MW of gas produced. A trend in scaling-up digestion conversion technologies is not foreseen due to the supply limitation. The digestion of sewage/manure material has a typical size limit below 1 MW but the capacity could be extended by the input of co-digestion material like organic residues or energy crops. Overall, the size of digestion plants reported in Table 2-3 should thus be seen as high estimates.

The efficiency of the digesters to convert biomass to biomethane depends on the type of biomass and the method of heat production needed for the digestion process.

The conversion efficiency for manure and sewage sludge is lower compared to the efficiency for other feedstock as there is a larger share of the feedstock that is difficult to digest. One of the improvement options of interest for increasing the conversion efficiency is the thermal pre-treatment of the feedstock. This could bring the conversion efficiency for manure and sewage sludge in the 50% range. Here we conservatively estimate that the conversion efficiency will remain equal at 40% (LHV) towards 2050.

For MSW, the efficiency depends on the collection method. Separate collection at the source will yield higher conversion rates (up to 70%) for the digestion route compared to on-site separation of the MSW stream. Here we conservatively assume a 60% efficiency which will remain equal towards 2050.

Table 2 - 3 Overview of technical performance of BE-CCS technologies for biomethane production assumed in this study (based on (ECN 2007; ECN 2008; FNR 2009; Urban, Girod et al. 2009; FNR 2010; Meijden 2010; Meijden, Bergman et al. 2010; Carbo 2011; ECN and KEMA 2011; ECN and KEMA 2011; OWS 2011))

Technology	View year	Capacity (MW_{final})	Net conversion efficiency	Carbon removal efficiency
Gasification	2030	250	68%	36%
Gasification	2050	500	70%	38%
Anaerobic digestion – EC and AR*	2030	10	60%	27%
Anaerobic digestion - EC and AR*	2050	15	60%	29%
Anaerobic digestion - MSW	2030	10	60%	27%
Anaerobic digestion - MSW	2050	15	60%	29%
Anaerobic digestion - Sewage/Manure	2030	10	40%	27%
Anaerobic digestion - Sewage/Manure	2050	15	40%	29%

*Energy Crops and Agricultural Residues

2.3.5 CO_2 capture during gas upgrading

Both the gasification and the digestion of biomass produce combustible gases. For gasification this gas is called "syngas" or "producer gas", for digestion it is called "biogas". Depending on the feedstock and conversion technology these intermediate product gases typically (may) contain methane, carbon dioxide, water, hydrogen sulphide, nitrogen, oxygen, ammonia, tars and particles. The concentrations of these contents depend on the used conversion method and the used biomass. Table 2 - 4 gives an overview of various gas types and their specifications. The syngas or biogas needs to be upgraded to improve the gas quality before it can be injected in a natural gas grid.

The upgrading process serves two goals: increasing the concentration of CH_4 and removing CO_2 and other components (IEA Bioenergy 2009). Depending on the upgrading technology, the removed CO_2 stream needs to be cleaned before it can be compressed, transported and stored.

Table 2 - 4 Specification of gas produced through anaerobic digestion and gasification of biomass Source: (Meijden 2010; Meijden, Bergman et al. 2010)(DMT Environmental Technology 2007))

Component	Entity	Digestion[8]	Gasification[9]
Methane CH4	Vol. %	45 - 70	10 – 12.5
Carbon dioxide CO2	Vol. %	30 - 45	16 – 20
Carbon monoxide CO	Vol. %	n/a	29 – 31
Nitrogen N2	Vol. %	1 - 15	1 – 20[10]
Hydrogen H2	Vol. %	-	16 – 20

The choice for an upgrading technology (and thus CO_2 removal) depends on different factors, such as the costs, the composition and characteristics (e.g. temperature, pressure) of the gas flow that has to be treated, the required purity of the CO_2 stream and the capacity (i.e. total gas flow). Table 2 - 5 shows the main advantages and disadvantages of the main upgrading technologies.

Scrubbing / absorption and PSA / adsorption ensure high gas quality, but both have as disadvantage significant CH_4 losses. Membrane and cryogenic also ensure high to very high gas quality, but require pre-treatment, have an uncertain long-term behaviour (membranes), only few project references (membranes and cryogenic), have high investment costs and are complex in use (cryogenic). Cryogenic separation of CO_2 can be combined with the production of liquefied biomethane, which may have co-benefits. The CO_2 becomes available as a liquid and the energy density of liquefied biomethane is much higher compared to gaseous biomethane. This provides opportunities for both transport of liquefied biomethane and for applying biomethane in the transport sector.

The optimal choice for CO_2 removal options varies with the conversion technology and the local situation. Important aspects are the required capacity (volume) and characteristics of the feed gas. Gasification is expected to take place on a large-scale (>500 MW), while digestion is expected to take place on smaller scale (<15 MW).

[8] The range in concentrations is caused by the differences in the input biomass.
[9] The range in concentrations is caused by the choice for fluidization agent: steam or air. For instance, when air is used, the concentration of nitrogen increases significantly.
[10] The range in N_2-content is caused by the possibility to use different types of gasification. Using air-blown gasification can cause a N_2-content of up to 20% in the product gas making the technology inappropriate for injection of biomethane in the natural gas grid. Indirect gasification lowers the nitrogen content considerably: it never exceeds 5% and can be as low as 1% (Carbo, 2012).

Table 2 - 5 Overview of advantages and disadvantages of gas upgrading technologies ((DMT Environmental Technology 2007; Ecofys 2008; Hullu, Maassen et al. 2008; Urban, Girod et al. 2008; IEA Bioenergy 2009; DMT Environmental Technology 2011))

Process	Advantages	Disadvantages
Scrubbing / absorption	High (water scrubbing) to very high (amine scrubbing) gas quality No pre-treatment necessary Proven technology Re-use of CO_2 possible Relatively low investment costs	Process water consumption Bulky process Water scrubbing: relatively high CH_4 losses (1 – 2 %)[11]. Amine scrubbing: waste gas treatment required and high heat demand.
PSA / adsorption	High gas quality Dry process No use of chemicals No demand of process water and no waste water Partial removal of N_2 and O_2 Proven technology	H_2S pre-treatment required CH_4 level not stable Complex process High maintenance effort needed High investment costs High CH_4 losses
Membrane	High gas quality (high gas quality requires long membranes). Dry process No use of chemicals Low mechanical wear Compact process Re-use of CO_2 possible Relatively low investment costs	Pre-treatment required Uncertain long-term behaviour Few references High energy demand
Cryogenic	High gas quality No use of chemicals No use of water Compact process Re-use of CO_2 possible Co-benefits when producing liquefied biomethane	Pre-treatment required Very high energy consumption High investment cost Complex process Only pilot plant references

[11] Typical installations have a “weak gas burner” to avoid methane emissions. The heat is used for and needed by the AD process.

2.3.6 CO_2 compression and transport

Following (IEA GHG 2011) we assume that CO_2 will be transported by pipelines. CO_2 transport by pipeline is considered a mature technology and is in most cases the most economic option. CO_2 transport by ship is technically feasible and has favourable economics in some cases, but is for simplicity reasons not included.

CO_2 transport by pipeline requires pressurization of the captured CO_2. The CO_2 is assumed to be compressed in a multistage compressor to the required transport pressure, which is typically above 100 bars.

CO_2 is typically released at atmospheric pressures from the digestion based routes. The energy requirement for compression from atmospheric pressure to 100 – 140 bars amounts to about 0.11-0.12 MWh_e/tonne CO_2. We assume equal compression power requirements for all routes.

2.3.7 CO_2 storage potential

It should be stressed that high uncertainties still exist regarding the estimation of storage capacity due to the use of incomplete data or simplified assumptions on geological settings, rock characteristics, and reservoir performance (Bradshaw, Bachu et al. 2006).

For the CO_2 storage potential we have used the same estimates as in (IEA GHG 2011), which gives storage estimates for the 7 world regions. These storage estimates reflect the theoretical storage capacity for three types of reservoirs:

1. Depleted hydrocarbon fields (oil & gas fields)
2. Aquifers
3. Unmineable coal seams

Because the estimations on global storage potential are first estimations (storage sites have to be assessed individually to assess the capacity more accurately and to know whether they are suitable for CO_2 storage), we included three estimations for each region: Low, Best and High. As default we used the 'Best' estimate to determine the technical BE-CCS potential.

2.3.8 Commensurability of biomass potential and CO_2 storage potential

Either the biomass resource or storage capacity can be the limiting factor that determines the technical potential. The biomass potential is expressed as an annual potential. The storage potential however is a finite resource which is given as the total amount of CO_2 that can be stored. To estimate the amount of CO_2 that we can store on an annual basis, we need to convert this total amount of storage capacity to an annual storage capacity. For the technical potential, we therefore assumed that 1/50 of the total storage capacity can be used annually, i.e. the saturation period of the total capacity is 50 years (at immediate full deployment). This is based on the conservative assumption that a project developer does not start a CO_2 injection activity if storage capacity is not assured for at least the entire lifetime of the energy conversion facility generating the CO_2. As this is a rather arbitrary assumption we consider an uncertainty range for this variable between 30 and 70 years in the sensitivity analysis in chapter 5.

2.3.9 Calculating the net greenhouse gas balance

A schematic representation of the greenhouse gas balance calculations is shown in Figure 2 - 6. The net greenhouse gas balance is calculated taking into account the uptake of CO_2 by the biomass during its growth, direct emissions from converting the biomass into energy carriers or during end-use, indirect emissions (for example GHG emissions from transporting biomass using fossil fuels) and the amount of (biogenic) CO_2 stored. In the total greenhouse gas balance we include the combustion of the biomethane. Distribution losses of the gas network are not taken into account.

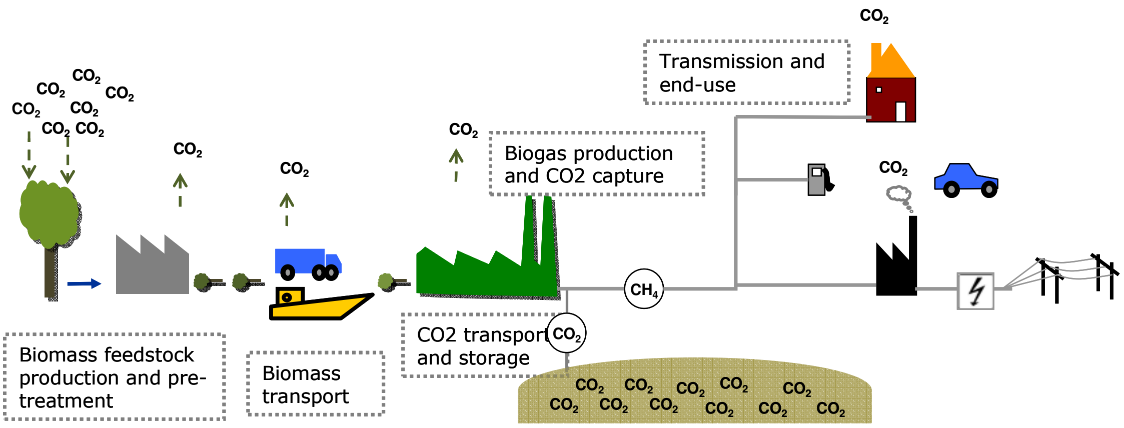


Figure 2 - 6 Schematic presentation of the system boundaries when calculating the greenhouse gas balance for biomethane production including CO_2 capture, transport and storage. The net greenhouse gas balance is determined by CO_2 uptake and emissions by processes in full chain, from biomass production to end-use.

Direct emissions and CO_2 uptake

Direct emissions are those emissions (either from fossil or biogenic origin) emitted during the conversion and end-use of the biomethane. The direct emission factor is assumed to be equal for all biomass resources and is set at 100 kg CO_2 /GJ (IPCC 2006)[12]. This emission factor is assumed to be equal to the amount of CO_2 that is taken up by the biomass during its growth, i.e. also 100 kg CO_2 /GJ. An uncertainty range between 85 and 117 kg CO_2/GJ is assumed, reflecting lower and higher estimates given in (IPCC 2006).

Indirect emissions

We also include greenhouse gas emissions emitted in the biomass supply chain, e.g. due to the use of fossil fuels in harvesting, preparing and transporting biomass. We include a greenhouse gas emission factor for the biomass supply chain ranging between 0 and 4.1 kg CO_2/GJ. For animal waste, sewage sludge and MSW we have excluded GHG emissions in the supply chain as these are here allocated to waste treatment and not to the production of biomethane.

CCS requires electricity from the grid for compression which results in the emission of CO_2. We have included GHG emissions that can be allocated to the use of electricity for the compression of CO_2. When electricity is consumed we assume an emission factor of 400 gCO_2 /kWh in 2030 and 300 gCO_2 /kWh in 2050 (IEA 2010).

Avoided emissions

Biomethane production from sewage sludge and animal manure is typically seen as a waste treatment option with important co-benefits. Biomethane production avoids CH_4 and other greenhouse gas emissions, which would have been occurred during waste treatment processes. For simplicity reasons we do not include these avoided emissions into our analysis. The effect, however, may be significant but is highly uncertain as it depends on whether biomethane production substitutes a GHG emitting disposal option. Implications of excluding these avoided emissions are discussed in more detailed in chapter 6 'Discussion'.

[12] IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories - Volume 2 – Energy. Internet: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html [Accessed 31-05-2010]

2.4 Results for the technical potential

Below, we present the technical potentials for the selected biomethane-CCS routes. The technical potential is expressed in primary and final energy (EJ/yr) and net greenhouse gas balance (Gt CO_2-eq).

2.4.1 Technical potential of gasification based biomethane production

An overview of the primary biomass and storage potentials in the different regions is given in Figure 2 - 7. The results show that the global primary energy potential increases from 73 EJ/yr in 2030 to 126 EJ/yr in 2050 (global natural gas production in 2009 amounted to almost 106 EJ/yr). There is no difference between 'World' and 'World2' indicating that in all regions the potential is restricted by the availability of biomass. Looking more into regional details the results show that the CO_2 storage potential in Oceania may become a limiting factor if storage capacity assessments prove to be too optimistic. For other regions the storage potential is not likely to become a limiting factor.

Figure 2 - 8 presents the global potential in terms of final energy (in EJ). The results show that the potential increases from 45 EJ/yr in 2030 to 79 EJ/yr in 2050. This increase is due to higher biomass potentials and the moderate increase in conversion efficiency.

Figure 2 - 9 shows that negative emissions can be achieved by biomethane production using bio-gasification in combination with CCS. Globally, in 2030 1.8 Gt of CO_2-eq per year can be removed from the atmosphere, growing to 3.5 Gt in 2050.

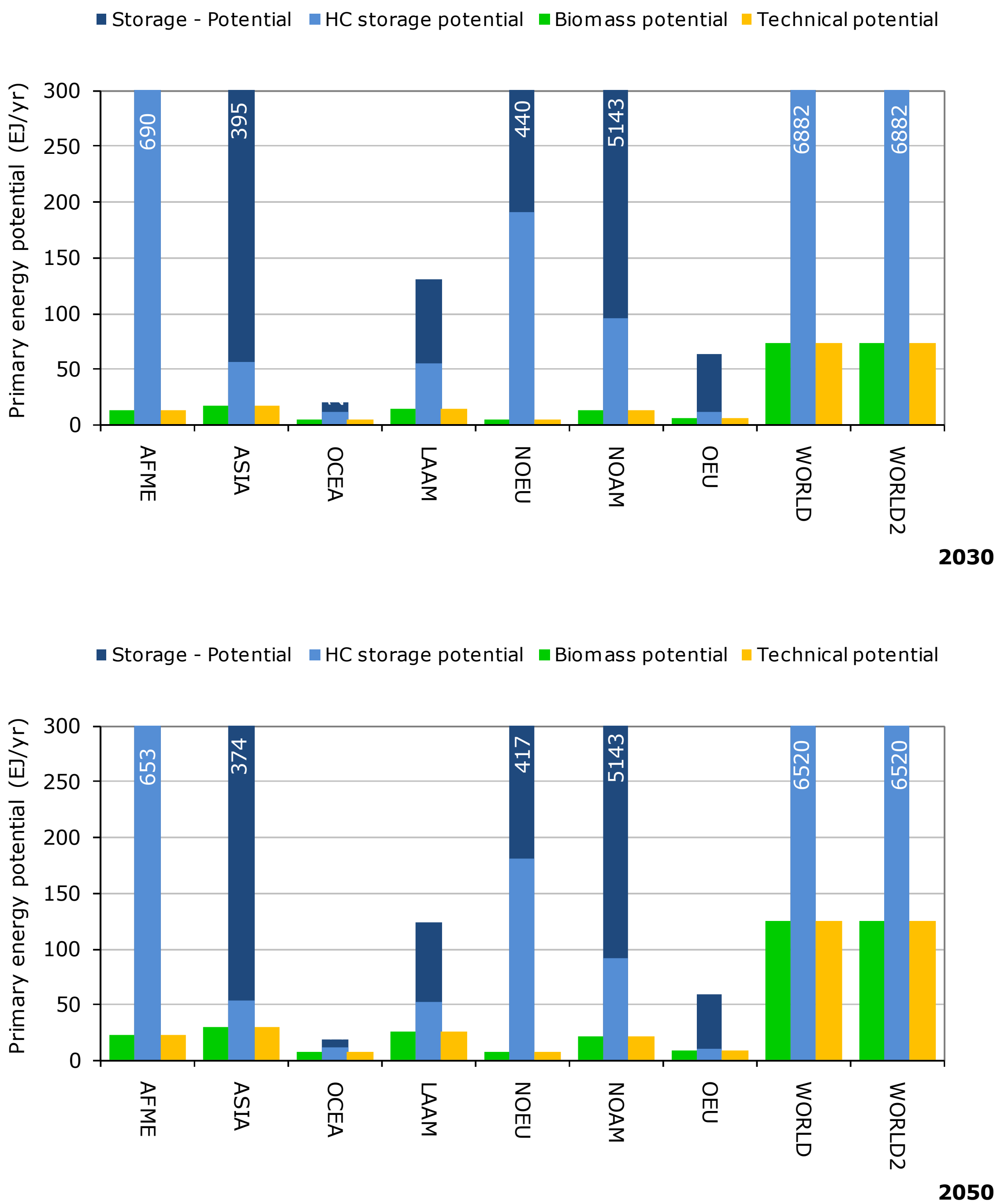
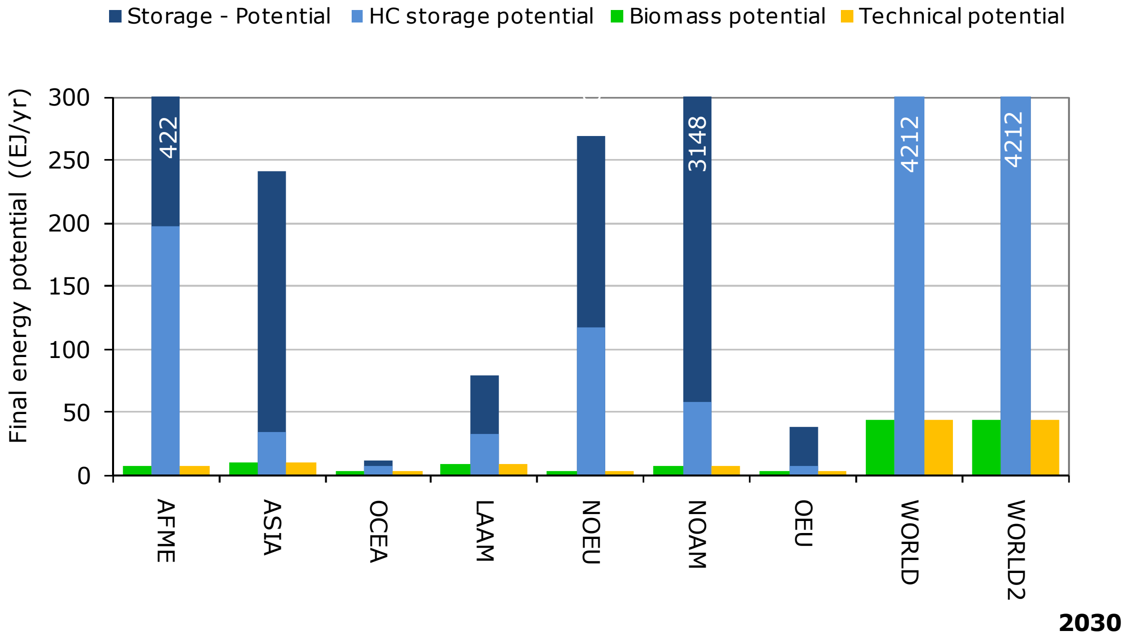


Figure 2 - 7 Primary biomass energy potential (EJ/yr) for gasification-CCS in 2030 and 2050. Orange bars indicate the resulting technical potential which is either limited by biomass (green bar) or total storage capacity (dark blue bar). The numbers in the figure represent the total storage potential expressed in energy equivalents (EJ/yr). Light blue share represents the CO_2 storage potential in (depleted) hydrocarbon fields. Note the y-axis cut-off and that the total storage potential is not always shown.



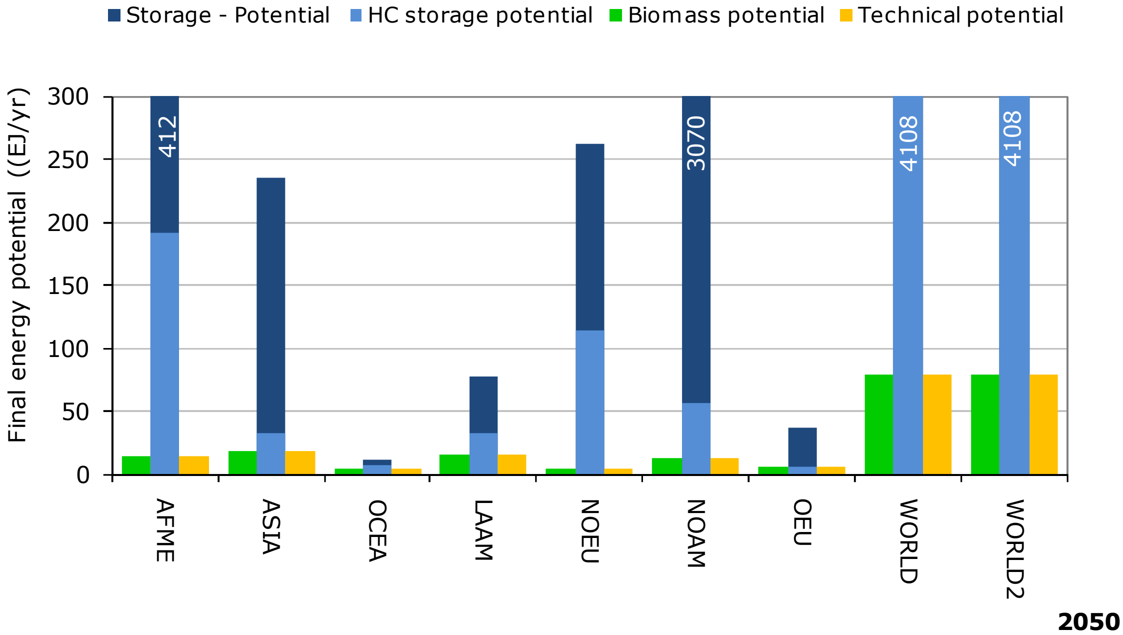
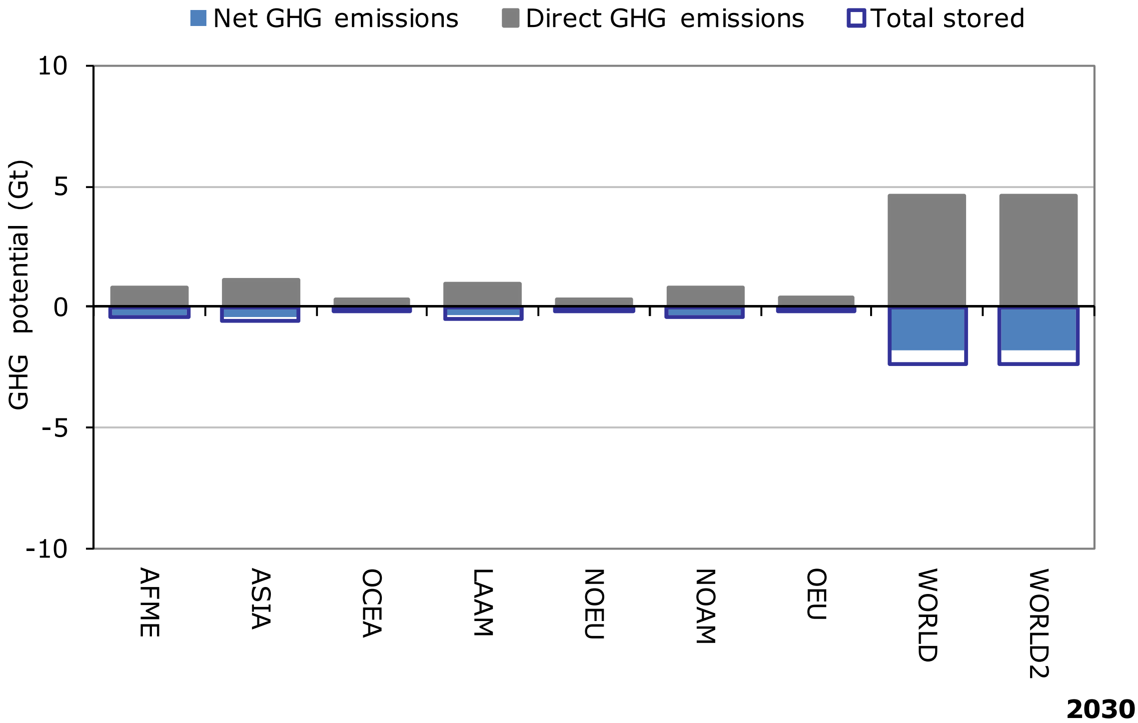


Figure 2 - 8 Final biomethane energy potential (EJ/yr) for gasification-CCS in 2030 and 2050. Orange bars indicate the resulting technical potential, which is either limited by biomass (green bar) or total storage capacity (dark blue bar). The numbers in the figure represent the total storage potential in EJ/yr. Light blue share represents the hydrocarbon storage potential. Storage capacity is based on 'best' estimate. "World2" technical potential excludes the possibility of inter-regional transport of biomass and CO_2.



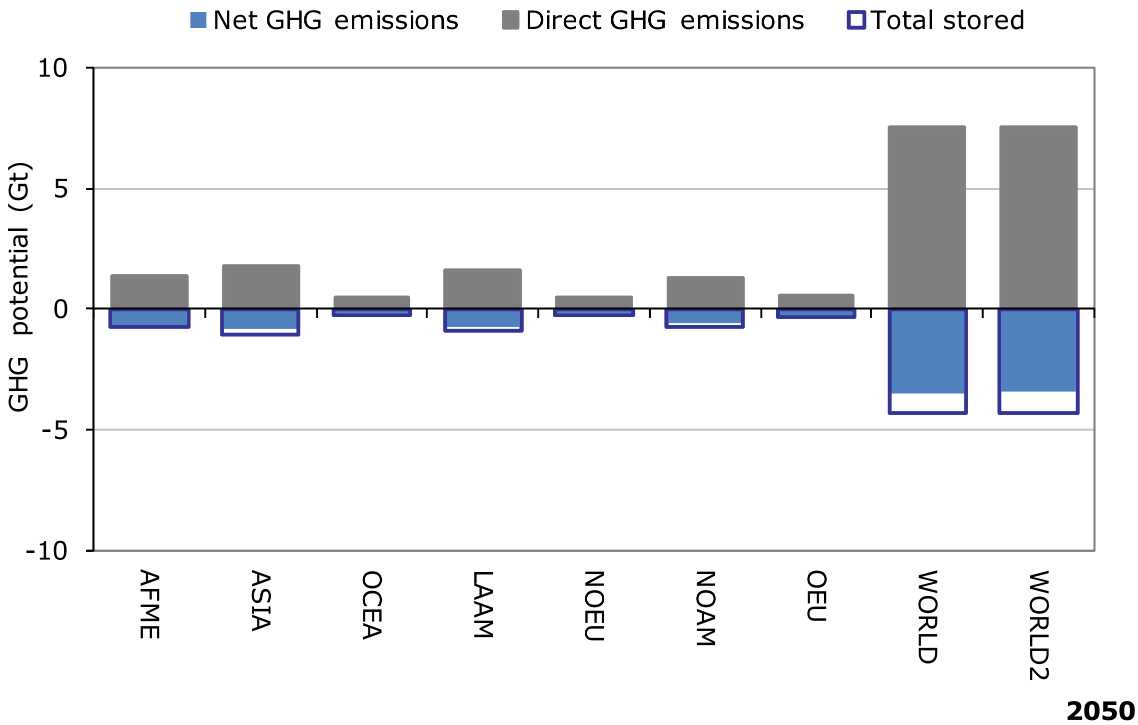


Figure 2 - 9 Net GHG emissions in Gt CO_2 eq for gasification-CCS in 2030 (above figure) and 2050 (below figure). Grey bars indicate the direct GHG emissions in the supply chain. Blue bars indicate the net emission balance, taking into account the uptake of CO_2 in the biomass and the storage of CO_2. Dark blue lined boxes indicate the amount of CO_2 stored.

2.4.2 Technical potential of the anaerobic digestion based biomethane route: energy crops and agricultural residues

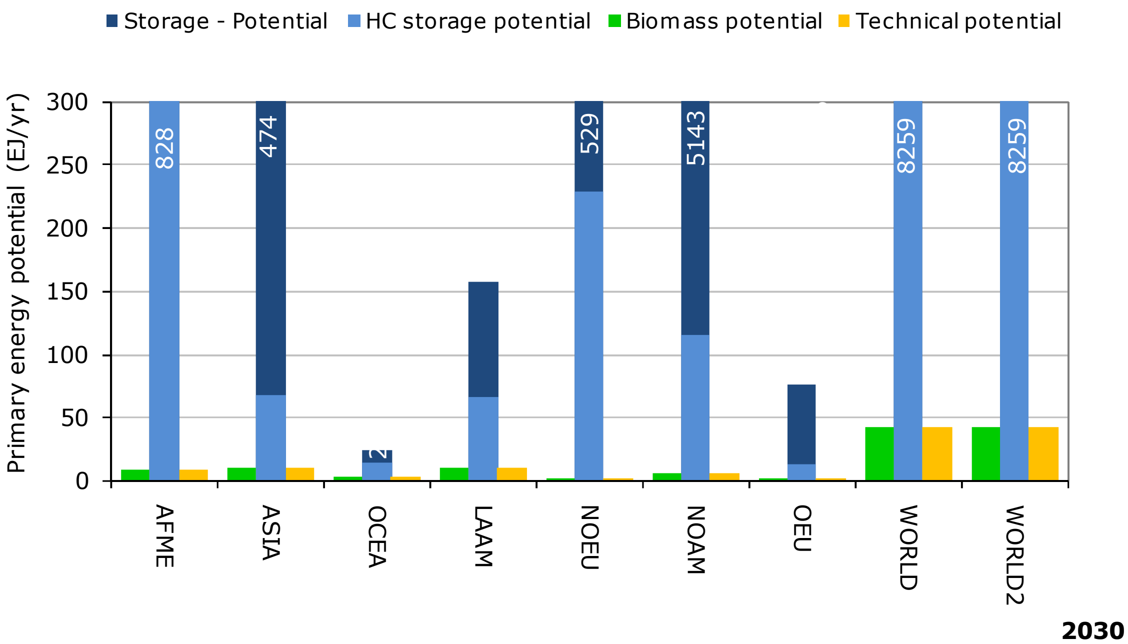
The primary biomass potential for biomethane production based on digestion of energy crops and agricultural residues in combination with CCS is given in Figure 2 - 10.

We see that the global primary energy potential for energy crops and agricultural residues increases from 43 EJ/yr in 2030 to 75 EJ/yr in 2050. (For reference, the global natural gas production in 2009 was almost 106 EJ.) This potential does not include the potential for MSW, sewage sludge and animal manure. As can be seen in the graph, the potential is restricted in all regions by the availability of biomass.

An uncertainty is introduced by the unknown share of lignocellulosic biomass in the total biomass supply. We assumed that 30% of the energy crops and agricultural residues is based on lignocellulosic and therefore not suitable for this route. We assume this high share as some lignocellulosic crops have high energy yields per surface area and will likely gain 'market' share in the future. Note that Van Vuuren et al (2009) assume that energy crops completely comprise of woody types, rendering a low to zero potential for this feedstock in this route.

The global potential for this combination of conversion technology and feedstock final in terms of energy is given in Figure 2-11. The potential increases from 26 EJ/yr in 2030 to 45 EJ/yr in 2050. This can be attributed to the increase in the primary biomass potential alone as we conservatively assume that the conversion efficiency will not improve towards 2050.

Figure 2-12 shows that negative emissions can be achieved in the anaerobic digestion route for energy crops and agricultural residues. Globally, between 1.1 and 2.1 Gt of CO_2-eq can be removed from the atmosphere per annum when deploying the full potential for this feedstock using this technology route.



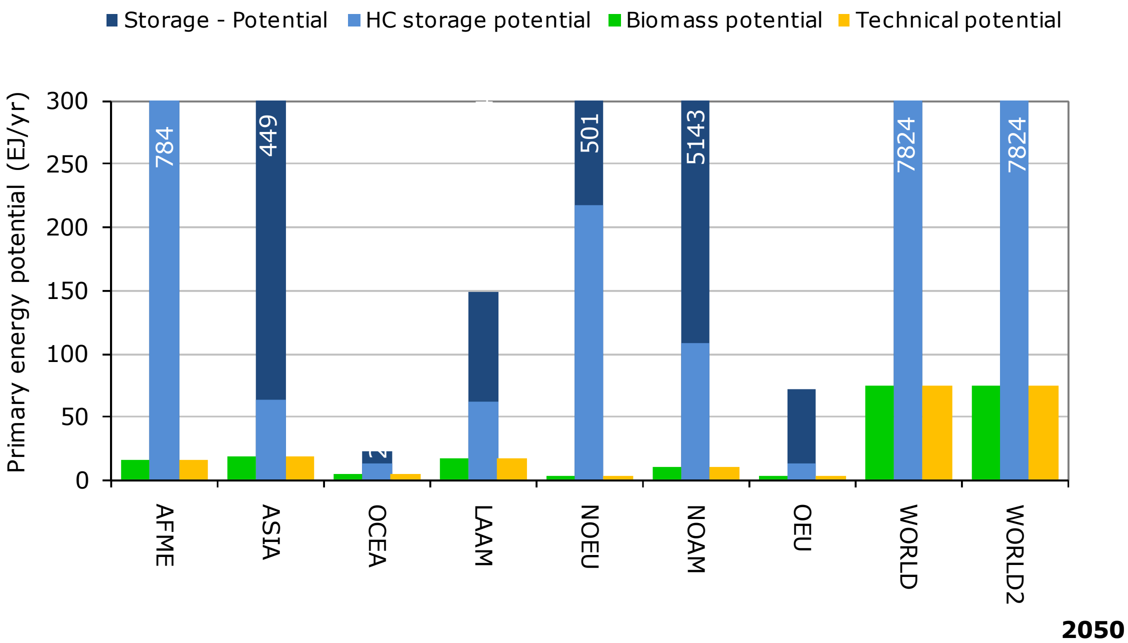
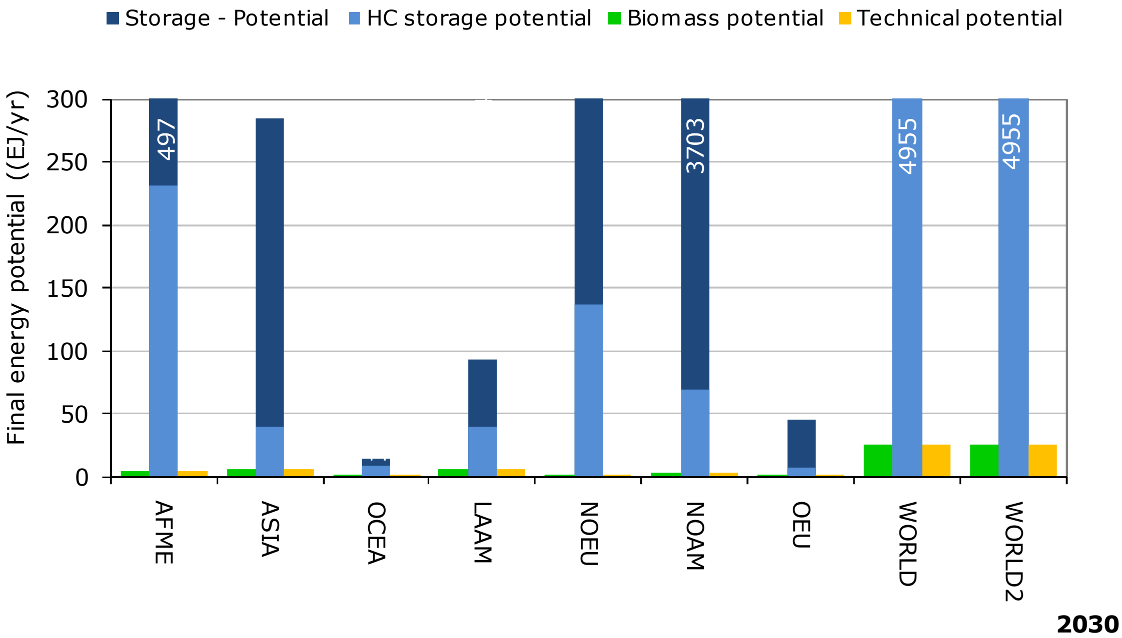


Figure 2 - 10 Primary biomass energy potential (EJ/yr) for digestion-CCS (EC and AR) in 2030 and 2050. Orange bars indicate the resulting technical potential which is either limited by biomass (green bar) or total storage capacity (dark blue bar). The numbers in the figure represent the total storage potential expressed in energy equivalents (EJ/yr). Light blue share represents the CO_2 storage potential in (depleted) hydrocarbon fields. Note the y-axis cut-off and that the total storage potential is not always shown.



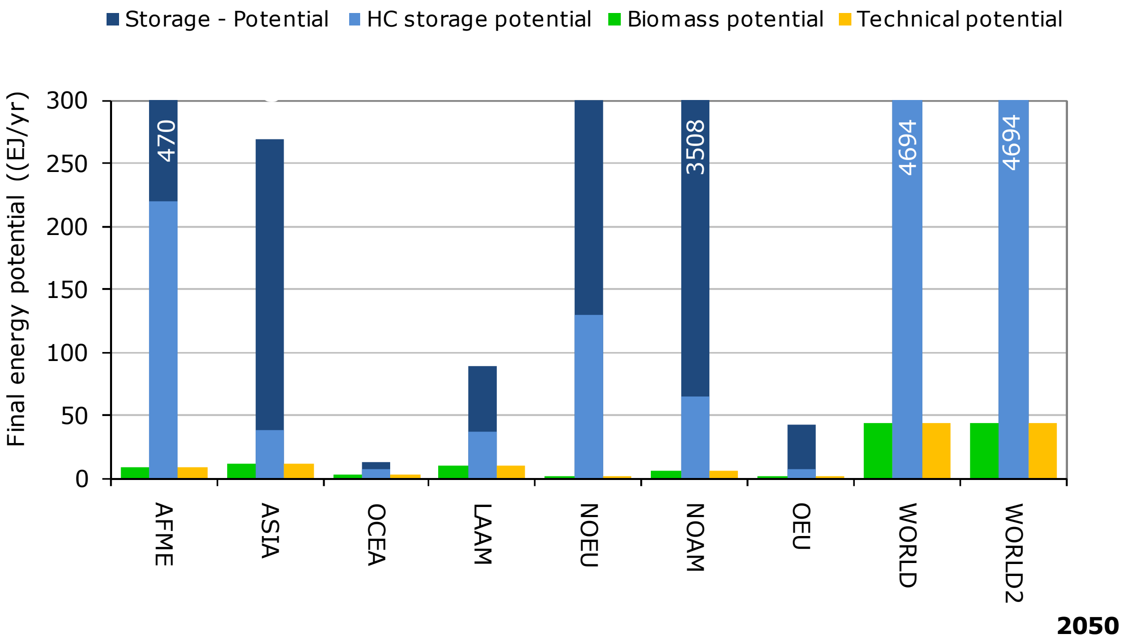


Figure 2 - 11 Final energy potential (EJ/yr) for digestion-CCS (EC and AR) in 2030 and 2050. Orange bars indicate the resulting technical potential, which is either limited by biomass (green bar) or total storage capacity (dark blue bar). The numbers in the figure represent the total storage potential in EJ/yr. Light blue share represents the hydrocarbon storage potential. Storage capacity is based on 'best' estimate. "World2" technical potential excludes the possibility of inter-regional transport of biomass and CO_2.

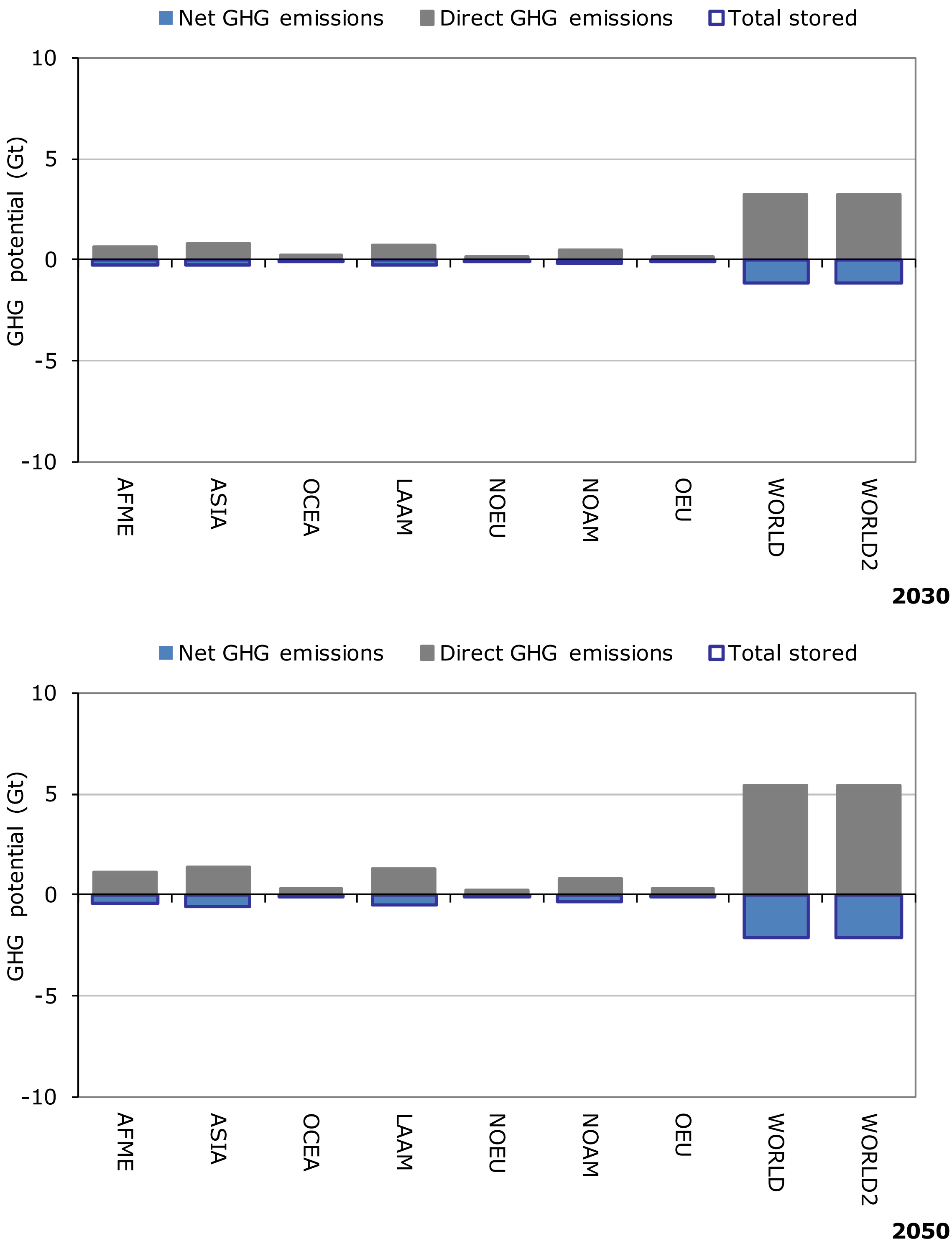


Figure 2 - 12 Net GHG emissions in Gt CO_2 eq for digestion-CCS (EC and AR) in 2030 and 2050. Blue bars indicate the net emission balance. Grey bars indicate the direct GHG emissions in the supply chain. Dark blue lined boxes indicate the amount of CO_2 stored.

2.4.3 Technical potential of the anaerobic digestion based biomethane route: biogenic municipal solid waste

The technical potential (primary energy) for anaerobic digestion of MSW is given in Figure 2-13. The figure shows that the global primary energy potential increases from 5.1 EJ/yr in 2030 to 10.6 EJ/yr in 2050, which is significantly smaller compared to the potential using energy crops and agricultural residues. Also for this technology route it holds that the technical potential is limited by the availability of biomass.

The global potential in terms of final energy is given in Figure 2-14. The potential increases from 3.1 in 2030 to 6.4 EJ/yr in 2050. This increase is due to the increasing availability of municipal solid waste; linked to the growth of human population (see Appendix B 1 for more details).

Figure 2-15 shows that negative emissions can be achieved in the anaerobic digestion route converting MSW. Globally, the results indicate that 0.1 Gt of CO_2 eq. can be removed per year from the atmosphere in 2030. In 2050 this has grown to 0.3 Gt of CO_2 eq due to the increasing MSW potential.

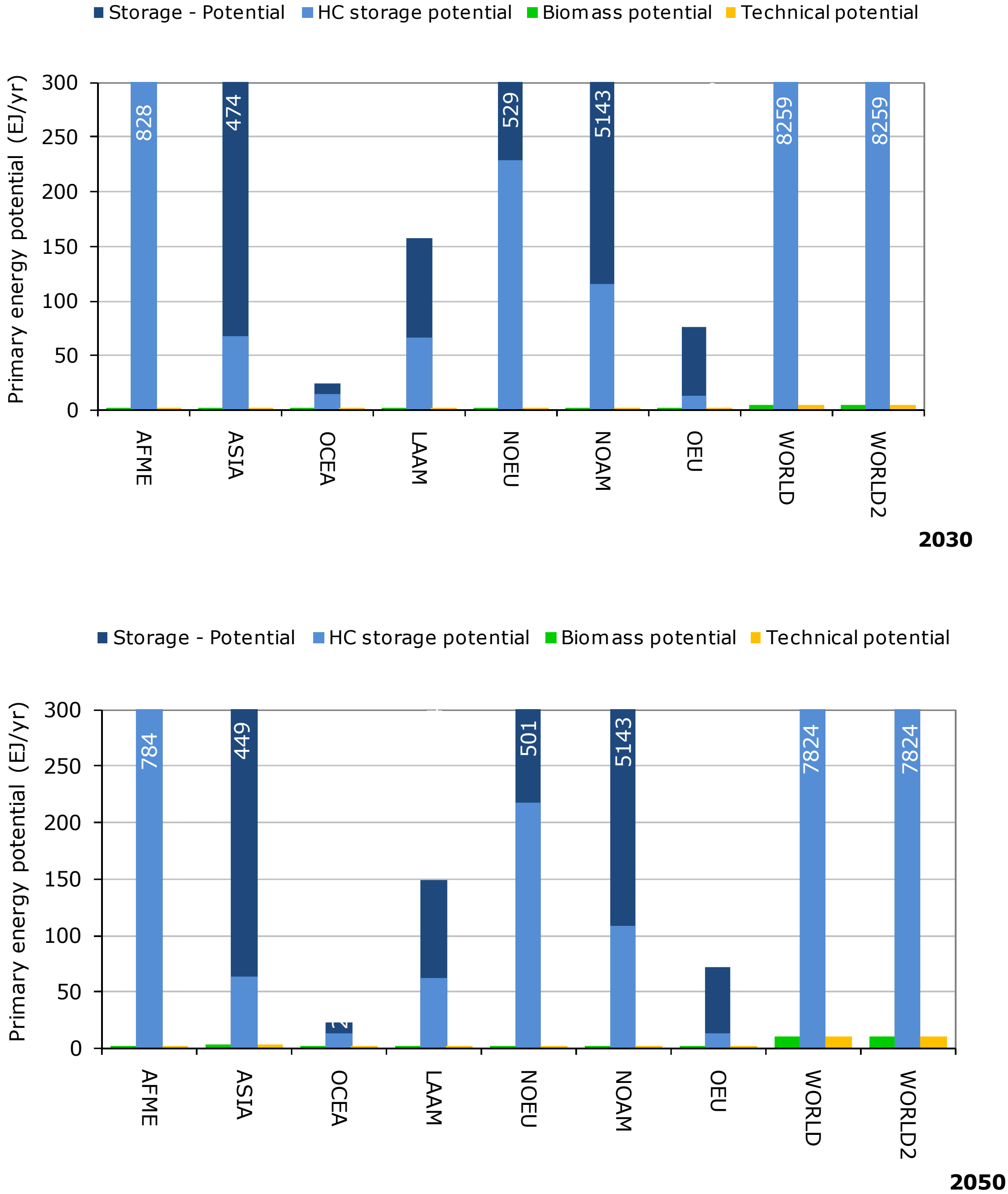
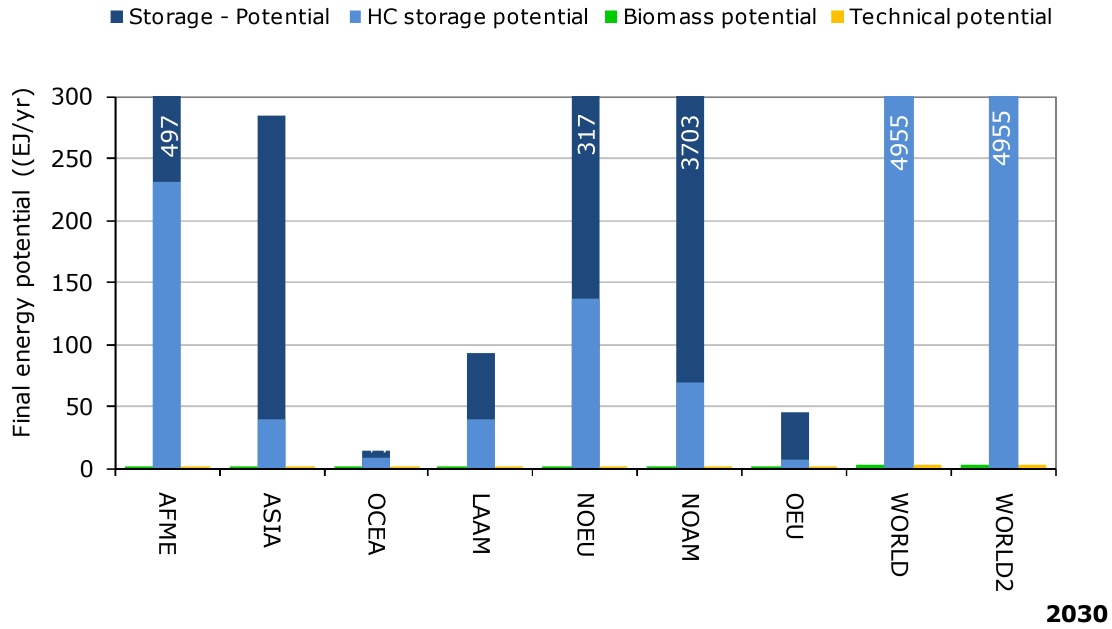


Figure 2 - 13 Primary biomass energy potential (EJ/yr) for digestion-CCS (MSW) in 2030 and 2050. Orange bars indicate the resulting technical potential which is either limited by biomass (green bar) or total storage capacity (dark blue bar). The numbers in the figure represent the total storage potential expressed in energy equivalents (EJ/yr). Light blue share represents the CO_2 storage potential in (depleted) hydrocarbon fields. Note the y-axis cut-off and that the total storage potential is not always shown.



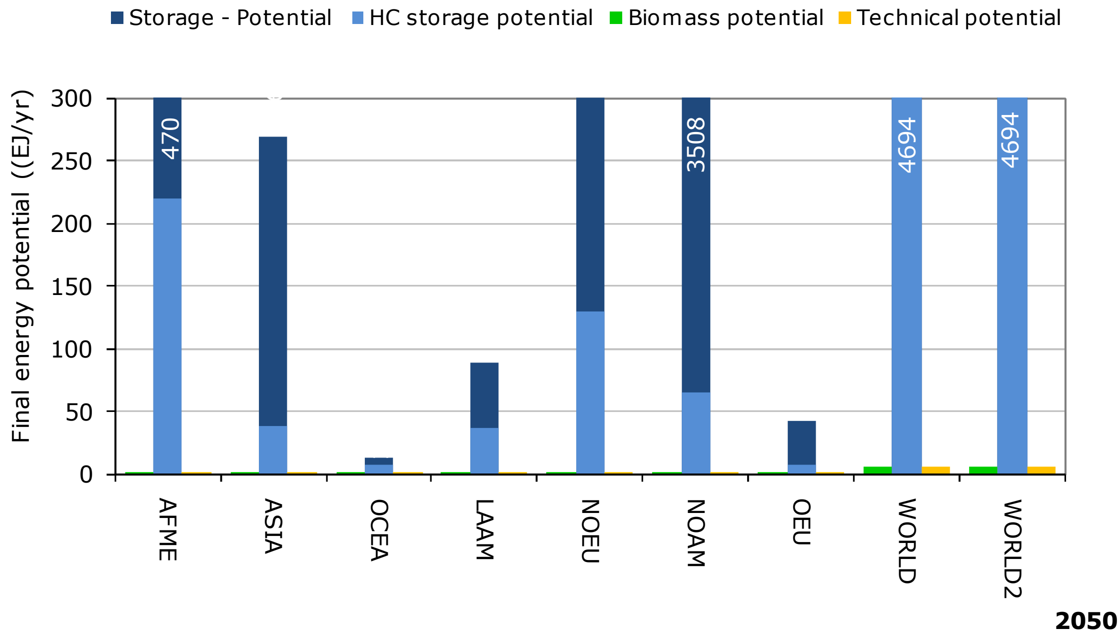
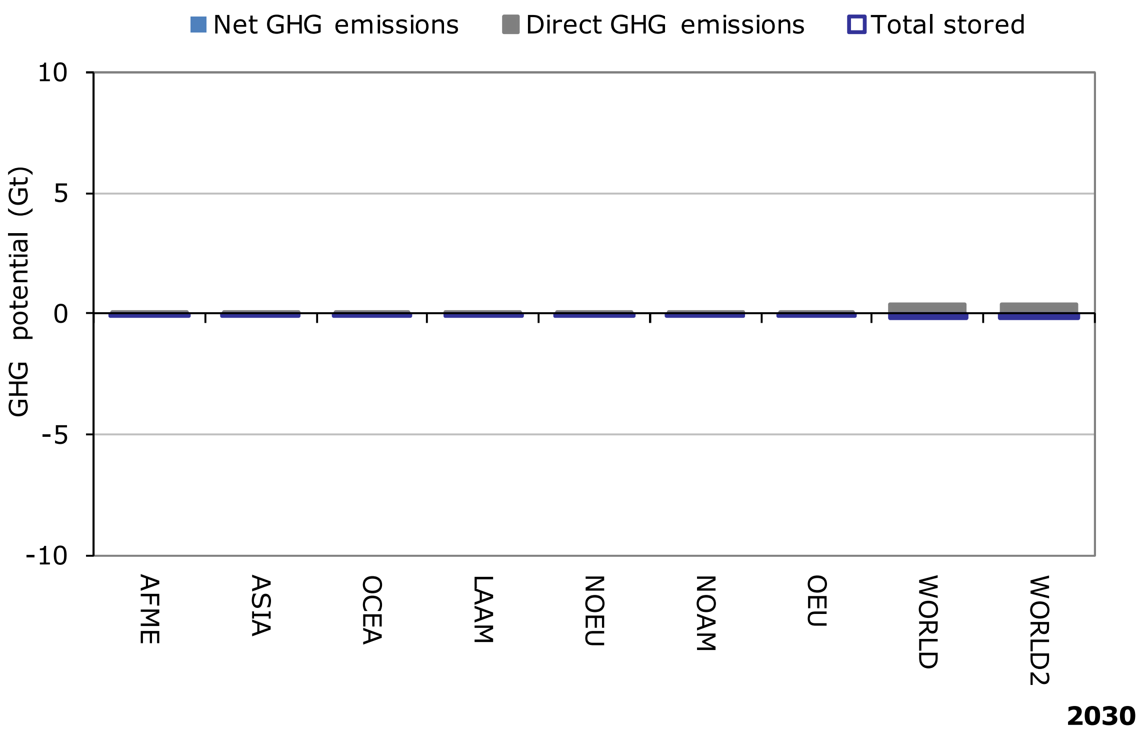


Figure 2 - 14 Final energy potential (EJ/yr) for the digestion-CCS (MSW) in 2030 and 2050. Orange bars indicate the resulting technical potential which is either limited by biomass (green bar) or total storage capacity (dark blue bar). The numbers in the figure represent the total storage potential in EJ/yr. Light blue share represents the hydrocarbon storage potential. Storage capacity is based on 'best' estimate. "World2" technical potential excludes the possibility of inter-regional transport of biomass and CO_2.



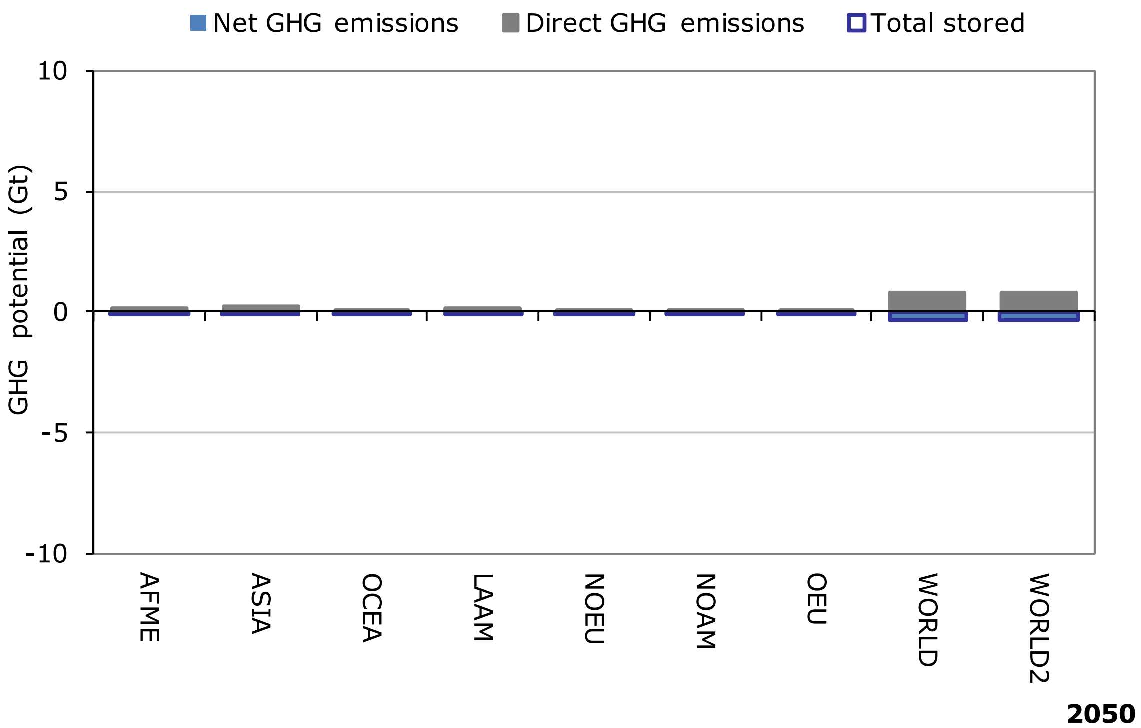


Figure 2 - 15 Net GHG emissions in Gt CO_2 eq for digestion-CCS (MSW) in 2030 and 2050. Blue bars indicate the net emission balance. Grey bars indicate the direct GHG emissions in the supply chain. Dark blue lined boxes indicate the amount of CO_2 stored.

2.4.4 Technical potential of the anaerobic digestion based biomethane route: animal manure and sewage sludge

The primary biomass potential for anaerobic digestion of animal manure and sewage sludge route is given in Figure 2-16.

We see that the global primary energy potential increases from 9.1 EJ/yr in 2030 and 16.1 EJ/yr in 2050. These potentials are limited by the availability of animal manure and sewage sludge and somewhat higher compared to the potential for applying digestion-CCS to municipal waste on a global scale.

The global potential in terms of final energy is given in Figure 2-17. The potential increases from 3 EJ/yr in 2030 to 5.5 EJ/yr in 2050. This increase is due to the increase in the availability of animal manure and sewage sludge. This potential is somewhat lower compared to the potential for digestion of MSW due to the lower conversion efficiency. The conversion efficiency for manure and sewage sludge is lower compared to the efficiency for other feedstock as there is a larger share of the feedstock that is difficult to digest.

Globally, in 2030, 0.2 Gt CO_2 eq can be removed from the atmosphere per annum, increasing to 0.4 Gt CO_2 eq in 2050. This analysis excludes the avoided methane emissions from sludge and manure without treatment; the global warming potential of methane is much higher than CO_2, so the overall greenhouse gas emission reduction potential of anaerobic digestion of manure and sewage sludge is probably significantly higher.[13]

[13] In the fourth assessment report of the IPCC (AR4), the global warming potential (100 year) of methane is estimated at 25.

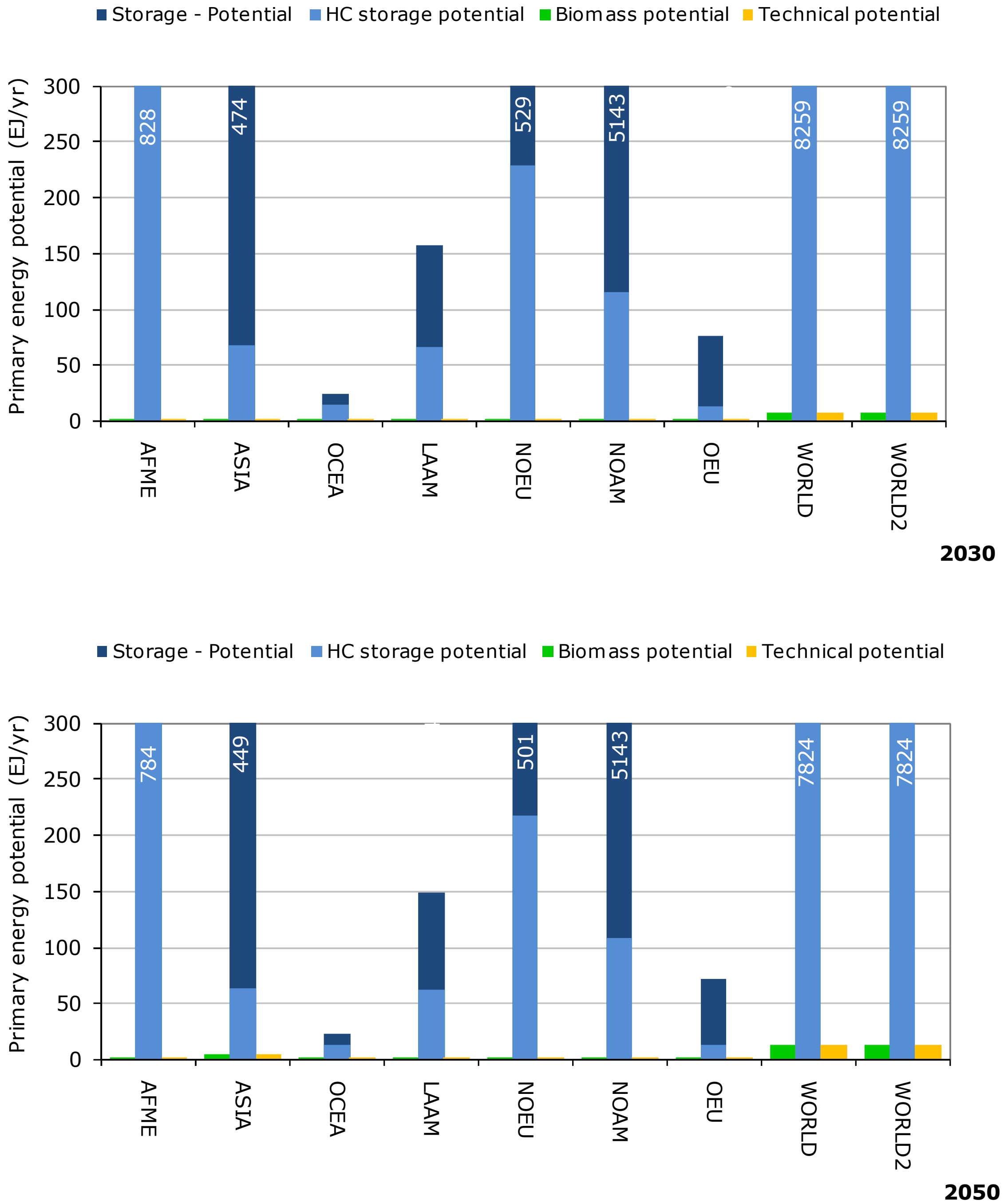
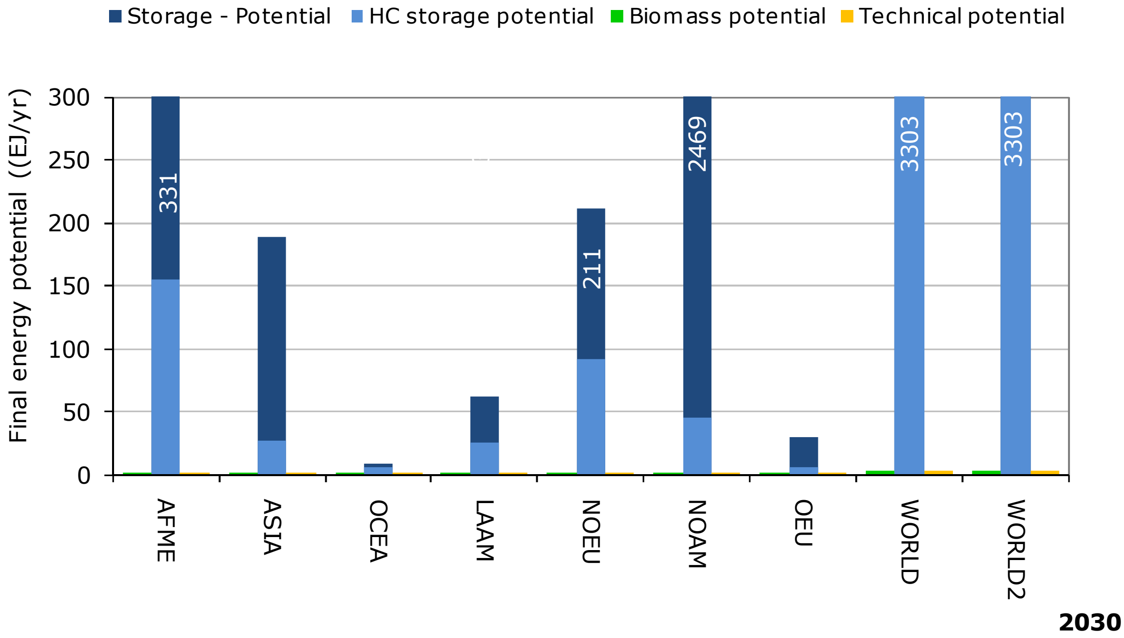


Figure 2 - 16 Primary biomass energy potential (EJ/yr) for digestion-CCS (animal manure and sewage sludge) in 2030 and 2050. Orange bars indicate the resulting technical potential which is either limited by biomass (green bar) or total storage capacity (dark blue bar). The numbers in the figure represent the total storage potential expressed in energy equivalents (EJ/yr). Light blue share represents the CO_2 storage potential in (depleted) hydrocarbon fields. Note the y-axis cut-off and that the total storage potential is not always shown.



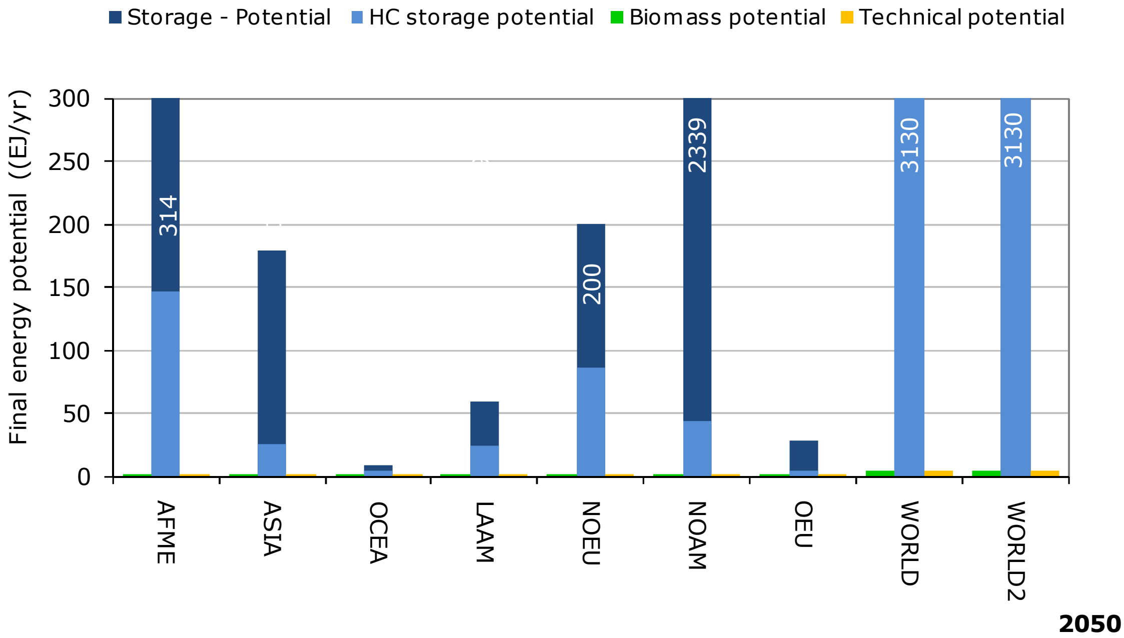
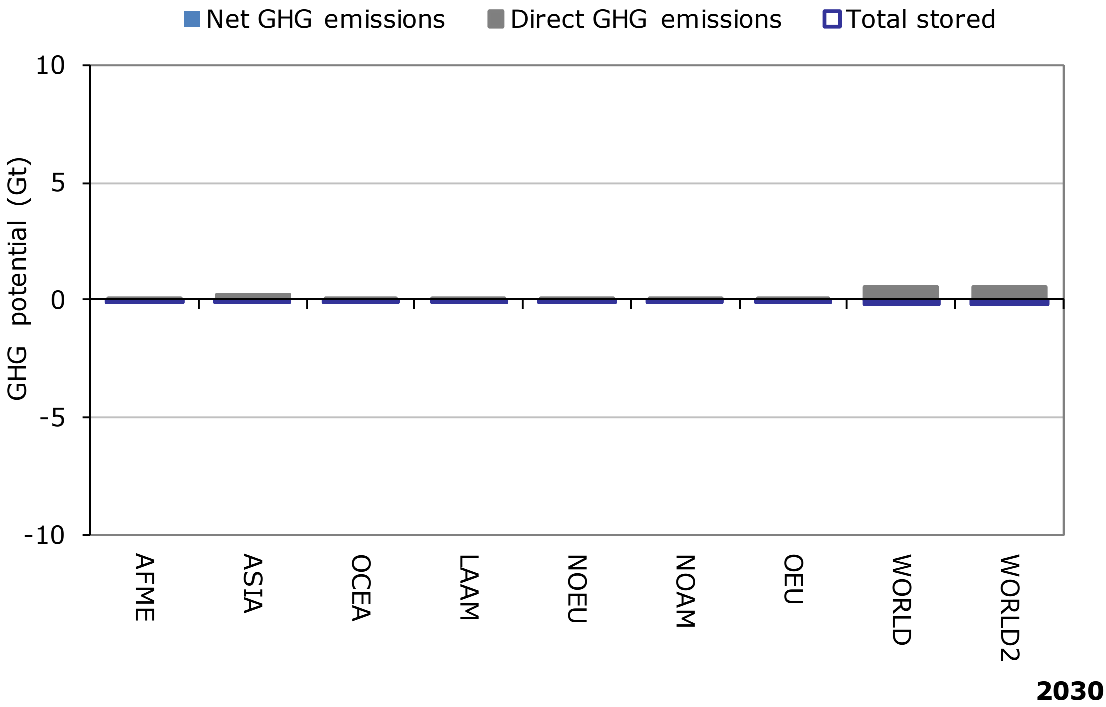


Figure 2 - 17 Final energy potential (EJ/yr) for the digestion-CCS (animal manure and sewage sludge) in 2030 and 2050. Orange bars indicate the resulting technical potential which is either limited by biomass (green bar) or total storage capacity (dark blue bar). The numbers in the figure represent the total storage potential in EJ/yr. Light blue share represents the hydrocarbon storage potential. Storage capacity is based on 'best' estimate. "World2" technical potential excludes the possibility of inter-regional transport of biomass and CO_2.



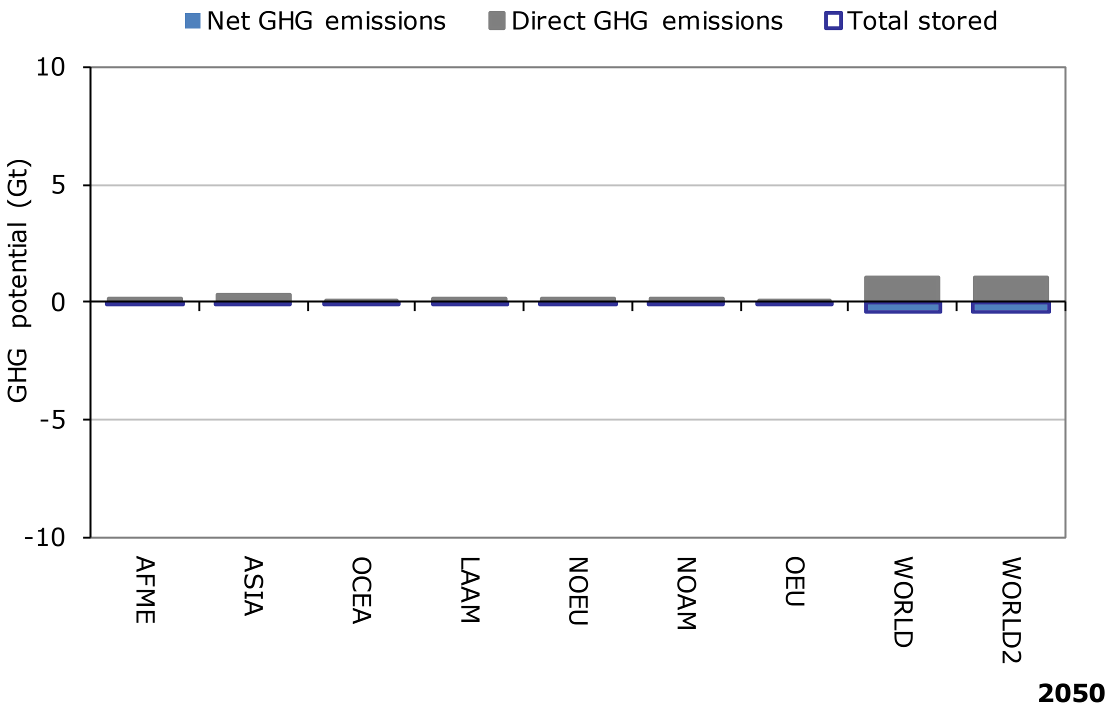


Figure 2 - 18 Net GHG emissions in Gt CO_2 eq for digestion-CCS (animal manure and sewage sludge) in 2030 and 2050. Blue bars indicate the net emission balance. Grey bars indicate the direct GHG emissions in the supply chain. Dark blue lined boxes indicate the amount of CO_2 stored.

3 Economic potential

In this chapter, we present the results of the economic potential for the biomethane-CCS technologies. The economic potential is determined by combining the cost supply curves for biomass resources with the conversion and CCS cost of the selected routes. The economic potential is defined as the amount of biomethane that can be produced at lower cost than natural gas.

3.1 Summary

The production costs of biomethane production via the digestion route are estimated at 5.8 € per GJ in 2030 when considering only the lowest cost category for the biomass feedstock and a CO_2 price of 50 €/tonne. Under the same assumptions, biomethane production costs via the gasification route are estimated at 13.5 € per GJ. The production costs in 2050 are somewhat lower: 5.5 and 13.1 €/GJ for digestion and gasification, respectively. The results indicate that cost of the primary biomass dominates the overall production cost with CCS, but the CO_2 price and natural gas price also have an important influence on the economic potential.

The results show that the economically most attractive route is the anaerobic digestion of sewage sludge and animal manure, with a potential up to 5.5 EJ in 2050. This is the only route that has an economic potential in a scenario with low natural gas prices (9.5 €/GJ including a CO_2 price premium). In a scenario with high natural gas prices (>14.2 €/GJ) there is an economic potential for both technology routes producing biomethane. The potential is largest for anaerobic digestion of MSW, which amounts to 6.4 EJ in 2050. The total for the digestion-CCS route is estimated at 14.3 EJ/yr in 2050. The total for the gasification-CCS route remains at 4.8 EJ/yr in 2050, predominantly due to higher feedstock cost with increasing demand for biomass.

Table 3 - 1 Overview of economic potential and production cost of selected BE-CCS routes

Technology	**Year**	**Economic Potential[1]**			**Production cost**			
Biomethane production		Min	Max	GHG	Lowest cost category[2]		Second cost category[3]	
		EJ/yr	EJ/yr	Gt/yr	€/GJ$_{final}$	€/MWh	€/GJ$_{final}$	€/MWh
Gasification	2030	0.0	2.7	-0.1	13.5	48.6	16.5	59.4
Gasification	2050	0.0	4.8	-0.2	13.1	47.0	16.0	57.5
Anaerobic digestion - EC and AR[4]	2030	0.0	1.4	-0.1	13.1	47.2	15.5	55.7
Anaerobic digestion - EC and AR[4]	2050	0.0	2.4	-0.1	12.9	46.6	15.3	55.0
Anaerobic digestion - MSW	2030	0.0	3.1	-0.1	11.4	41.2		
Anaerobic digestion - MSW	2050	0.0	6.4	-0.3	11.3	40.6		
Anaerobic digestion - Sewage/Manure	2030	3.0	3.0	-0.2	5.8	20.7		
Anaerobic digestion - Sewage/Manure	2050	5.5	5.5	-0.4	5.5	19.9		
Fossil reference								
Natural gas price in low price scenario					9.47	34.10		
Natural gas price in high price scenario					14.2	51.10		

[1]Economic potential is the annual amount of biomethane (EJ/yr) that can be produced at lower cost than the expected natural gas price. The maximum economic potential is determined by comparing the production cost with natural gas prices in a high price scenario (from WEO Current Policies Scenario), and the minimum potential by comparing with gas prices in a low gas price scenario (from the WEO 450 ppm scenario).

[2]Lowest cost category represents a biomass price at factory gate of 5.2 €/GJ and CO_2 price of 50 €/t. Cost for MSW and Sewage/Manure are assumed to be zero.

[3]Second cost category represents a biomass price at factory gate of 7.0 €/GJ and CO_2 price of 50 €/t.

[4]Energy Crops and Agricultural Residues.

3.2 Determining the economic potential

The economic potential is defined as the biomethane potential that can be produced at lower cost than reference natural gas prices taking into account a CO_2 price premium depending on the CO_2 price. In the first report we compared production cost of bio-electricity generating technologies with CCS to that of coal fired power plants with CCS. We also compared the production cost of biofuel production with CCS to the price of fossil gasoline and diesel. Here we compare production cost for biomethane with a natural gas price range. The cost estimates for the biomass feedstock supply chain for energy crops, agricultural residues and forestry residues are taken from the main report and remain unchanged. For the digestion route, we have assumed zero costs for municipal solid waste and manure & sewage sludge as these types of feedstock are considered waste and need to be disposed of anyway.

We first construct biomethane regional supply curves, by calculating the maximum potential of biomethane that can be produced at a certain cost level. The costs include biomass supply cost, conversion cost, CCS cost and a CO_2 price (base case: 50 € per tonne of CO_2). Subsequently, the economic potential for the selected bio-methane routes is then calculated by determining the amount of biomethane that can be produced at lower costs than the reference natural gas price. This potential can be expressed in primary and final energy, and in net greenhouse gas emissions.

For 2030, we use natural gas price estimates from the World Energy Outlook 2010 (IEA 2010). We consider both high and low natural gas price estimates. The 'high' prices are based on the WEO Current Policies Scenario and the 'low' prices are from the WEO 450 ppm scenario. For 2030, the WEO does provide consistent price estimates. For this study, we assume that gas prices in 2050 remain unchanged compared to the estimates provided for 2030.

Natural gas prices vary per region and range between 6.7 and 11.4 €/GJ without a CO_2 price premium. Including a CO_2 price premium, with a CO_2 price of 50 € per tonne, the natural gas price reference ranges between 9.5 and 14.2 €/GJ. In the 'high' price scenario we assume 14.2 €/GJ as upper price level. The 'low' natural gas price scenario uses 9.5 € per GJ.

The upper estimate of the economic potential is then determined by comparing the biomethane-CCS production cost with the highest natural gas price (and the CO_2 costs[14]). The lower estimate for the economic potential is estimated using the low natural gas prices (again including CO_2 costs).

3.3 Economic performance of BE-CCS routes

To estimate the economic potential, the costs for biomethane production need to be determined. For the cost estimation, we distinguish the following elements:

- The biomass supply chain, which includes the production, transport and pre-treatment cost of the biomass.
- The biomethane production step including CO_2 removal, which includes the investment cost and operation and maintenance cost.
- The remainder of the CCS chain, which includes the cost of transport and storage of CO_2.

[14] i.e. the emission factor of natural gas (in tonne/GJ) multiplied by the CO_2 price (in EUR/tonne)

The cost of these elements and the difference per technology route will be discussed below.

Biomass production, pre-treatment and transport

For the gasification route the cost of biomass production, pre-treatment and transport for energy crops, forestry residues and agricultural residues are taken from (IEA GHG 2011); details are presented in Appendix A.

For the production step we have developed cost-supply curves on a regional level. The cost-supply curves are based on four steps, or cost categories[15], as presented in the table below. For example, at a global level in 2030 about 24 $EJ_{primary}$/yr can be produced per year at a price below 7 €/GJ_{pellet}.

Table 3 - 2 Cost and price of biomass potential for energy crops, agricultural residues and forestry residues used in the gasification route.

	Unit	Cost category biomass potential			
Cost element per category		**I**	**II**	**III**	**IV**
Biomass production cost	€/$GJ_{primary}$	0.8	1.7	3.3	41.5
Ratio price/cost	-	4	3	2.5	1.2
Price of biomass	€/$GJ_{primary}$	3.3	5.0	8.3	49.8
Price incl. densification and transport	€/$GJ_{primary}$	4.7	6.3	9.6	51.2
Price of biomass pellets at factory gate	€/$GJ_{pellets}$	5.2	7.0	10.7	56.9
Cumulative biomass potential		**I**	**II**	**III**	**IV**
Global potential EC, AR and FR in 2030	$EJ_{primary}$	4	24	40	73
Global potential EC, AR and FR in 2030	$EJ_{primary}$	8	42	68	126

As can be seen in the table above the biomass pre-treatment and transport makes up a significant part of the biomass supply chain cost for the route based on gasification. Using ranges presented in the study from (van Vliet, Faaij et al. 2009) for the cost of local transport, densification and ocean shipping we have estimated the cost of pre-treatment to be between 0.4 and 1.7 €/GJ.[16] The cost of transport is largely determined by the distance and transport mode. The cost of inland train and push

[15] For residues, both agricultural and forestry, we used the assumption from Hoogwijk et al. (2010) that 10% of the potential is available at costs below 0.8 €/GJ and 100% below 41.5 €/GJ. All costs/prices are presented in $€_{2010}$ unless otherwise stated.

[16] Cost of pre-treatment (densification and torrefaction) ranges between 0.4 and 1.5 $€_{2005}$/GJ according to Van Vliet et al. (2009)

tugs (up to 300 km) ranges between 0.1 and 0.4 $€_{2005}$/GJ. Cost of ocean shipping (up to 12 000 km) is approximately 0.1-0.2 $€_{2005}$/GJ. Total costs of transport are estimated at 0.2-0.6 €/GJ. The combined costs for pre-treatment and transport range from 0.6 to 2.1 €/GJ.

For our base-case calculations in the gasification route we assume therefore total costs for pre-treatment and transport cost at 1.3 €/GJ. Following (Luckow, Dooley et al. 2010), we assume that this cost premium will apply on all biomass supply in the gasification route.

Table 3 - 3 Overview cost assumptions on biomass densification/pre-treatment and transport for both technology routes. All cost are in $€/GJ_{primary}$

Route	Feedstock	Activity/process	Low	Base case	High
Gasification	-Energy crops -Agricultural residues -Forestry residues	Biomass densification/pre-treatment	0.4	0.9	1.5
		Biomass transport	0.2	0.4	0.6
Digestion	-Energy crops -Agricultural residues	Biomass transport	0.6	1.2	4.5
	-Municipal Solid Waste -Sewage sludge and animal manure	Biomass transport	0	0	0

In the digestion route we take the regional cost-supply curves for energy crops and agricultural residues albeit with different cost assumptions regarding the pre-treatment and transport cost. Because anaerobic digestion requires wet biomass, no extensive pre-treatment of the biomass is required for this technology. For anaerobic digestion of energy crops and agricultural residues, we assume the transport costs to be three times higher than for transport of dried and densified biomass, mainly due to the high water content. Cost details are provided in Table 3 - 3.

For MSW, sewage sludge and animal manure we assume a conservative zero feedstock cost as these biomass sources are considered 'waste'. Often negative costs are associated with waste treatment (i.e. gate/tipping fees for waste treatment). In the future these waste streams may turn into valuable feedstock and negative cost may change into positive cost, increasing the production cost of biomethane (for the manufacturer). It should be noted that the price setting of 'waste streams' is highly uncertain.

For MSW, sewage sludge and animal manure, we do not attribute transport costs to the feedstock; we assume that this 'waste' has to be treated anyway and that this treatment can be combined with a digester. The costs of transport are thus allocated to waste treatment and not to the production of biomass, and biomethane.

For both technology routes the fuel costs are determined by the price of primary biomass supply and the conversion efficiency, which varies per technology. An overview of efficiencies is given in Table 3 - 4.

Biomethane production cost: Investment and operation & maintenance cost
The most important remaining, next to fuel cost, elements in the total production cost of biomethane are the investment cost for the biomass conversion and CO_2 capture installation, and operation & maintenance cost. We do not include additional infrastructure costs that might be required to inject the biomethane into the natural gas infrastructure as these costs are typically low.

Table 3 - 4 presents the total investment costs for the production of biomethane, including CO_2 removal. It should be noted that the reported CO_2 capture costs only refer to the purification and compression step of the CO_2 stream as the removal of CO_2 is already an integral process step in the biomethane production process.

Investment costs for biomass gasification processes are scarce. ECN estimates the investment costs for the MILENA gasifier at 1,100 €/kW (Carbo, Smit et al. 2010). We use cost estimate for a relative large sized gasification plant of 500 MW_{th}.

The investment costs of digestion plants depends on the type of biomass used. In principle the type of installation does not depend on the type of feedstock, however, installations converting agricultural waste and energy crops are typically larger reducing the specific investment cost. An exception is digestion of MSW for which a different - more expensive - type of digester is required. MSW requires also more intensive pre-treatment (see section 2.3.4). An important part of the investment costs of all digesters can be allocated to upgrading the biogas to biomethane.

Operation and maintenance (O&M) cost are here calculated as a percentage of investment cost. Typical values are presented in Table 3 - 4 indicating that O&M costs vary per type of conversion process. Electricity consumption for compression is also included in the O&M costs assuming an electricity price of 40 €/MWh and compression energy requirement of 0.12 MWh/tonne CO_2.

With this information it is possible to calculate the cost per GJ_{final} for investment, and operation and maintenance under certain assumptions on the amount of full load hours per year and the discount rate translated into an annuity factor.

The cost per GJ_{final} (excluding fuel cost) is expressed as:

Installation, O&M cost (€/GJ) = $$\frac{(IC \times \alpha + OM)}{FLH} \times C \qquad (2)$$

With:

IC = Investment cost of conversion installation (including CO_2 capture costs (€/kW)

α = Annuity (based on discount factor of 10 %)

OM = O&M costs per kW per year (for CO_2 capture installation and conversion installation)

FLH = Full Load Hours

C = Conversion factor to GJ: 1000/3.6 = 278

Table 3 - 4 Overview of performance and cost of biomethane production technologies. Cost estimates are based on (ECN 2007; ECN 2008; FNR 2009; Urban, Girod et al. 2009; ECN and KEMA 2010; FNR 2010; Meijden 2010; Meijden, Bergman et al. 2010; Carbo 2011; ECN and KEMA 2011; ECN and KEMA 2011; OWS 2011)

Technologies with CO_2 capture	**View year**	**Conversion eff. (LHV)**	**Carbon removal eff.**	**Specific investment cost €/kWfinal**		**Annual operation and maintenance cost €/kWfinal**		**Operation and maintenance cost (in % of investment cost)**		**Generation cost (fuel excluded) €/GJfinal**	
				Total (incl. capture)	Capture	Total (incl. capture)	Capture	Conversion	Capture	Total (incl. capture)	Capture
Gasification	2030	68%	36%	1140	40	108	10	9%	6%	7.95	0.50
Gasification	2050	70%	38%	1132	32	108	10	9%	6%	7.91	0.46
Anaerobic digestion – EC and AR	2030	60%	27%	1053	103	98	13	9%	6%	7.27	0.82
Anaerobic digestion – EC and AR	2050	60%	29%	1043	93	97	12	9%	6%	7.22	0.77
Anaerobic digestion - MSW	2030	60%	27%	1753	103	193	13	11%	6%	13.15	0.82
Anaerobic digestion - MSW	2050	60%	29%	1743	93	192	12	11%	6%	13.10	0.77
Anaerobic digestion - Sewage/Manure	2030	40%	27%	1285	135	103	18	7%	6%	8.30	1.12
Anaerobic digestion - Sewage/Manure	2050	40%	29%	1272	122	103	18	7%	6%	8.25	1.06

Investment costs are very sensitive to inflation of prices of raw construction materials, e.g. steel and cement. Note that we did not adjust the investment cost to inflation indices. Costs are based on 8000 full load hours per year and a depreciation period of 30 years.

Conversion costs include the onsite pre-treatment (e.g. mechanical separation) of biomass. Capture costs include the cost of compression assuming an electricity price of 40 Euro/MWh and 125 kWh/tonne CO_2 compression energy. Capture efficiency is given as the percentage of carbon in feedstock that is captured, transported and stored as CO_2.

CO_2 transport and storage costs

Here we assume that all CO_2 is transported by pipeline. The costs of CO_2 transport depend strongly on the terrain conditions (including elevation and artworks), distance, and the amount of CO_2 transported. The clustering potential of sources and sinks is an important factor in influencing transport cost (IEA GHG 2009). Clustering is of importance for biomethane-CCS technologies. This holds especially for the digestion based route with CCS as digesters are typically small scale conversion systems (<15 MW, <0.03 Mt/yr). To reach economies of scale and to reduce cost for the gas treatment and transport, biogas from digesters can be gathered before upgrading (including CO_2 capture). Upgrading and connection to the natural gas and CO_2 infrastructure is then more centralised.

It is however beyond the scope of this study to provide a detailed analysis of clustering sources. Instead we use a global range of CO_2 transport cost covering the range of cost found in IEA GHG (IEA GHG 2009) for the various regions. The implications of this assumption for both biomethane-CCS routes are discussed in section 6.

To determine the cost of transport and storage of CO_2 per GJ of biomethane we use cost figures expressed in Euro per tonne. The performance data in Table 3 - 4 tells us how much CO_2 is captured, transported and stored per GJ_{final} by combining the conversion and carbon removal efficiency, and generic emission factor of 100 kg $CO_2/GJ_{primary}$. The amount captured per GJ_{final} is then multiplied by the cost of CO_2 transport and storage.

The global cost range for CO_2 transport is estimated to be between the 1 and 30 €/tonne. The default value assumed here is 5 €/tonne. For CO_2 storage we assume the costs to range from 1 to 13 € per tonne. We assume a default value of 5 € per tonne.

Total biomethane production cost

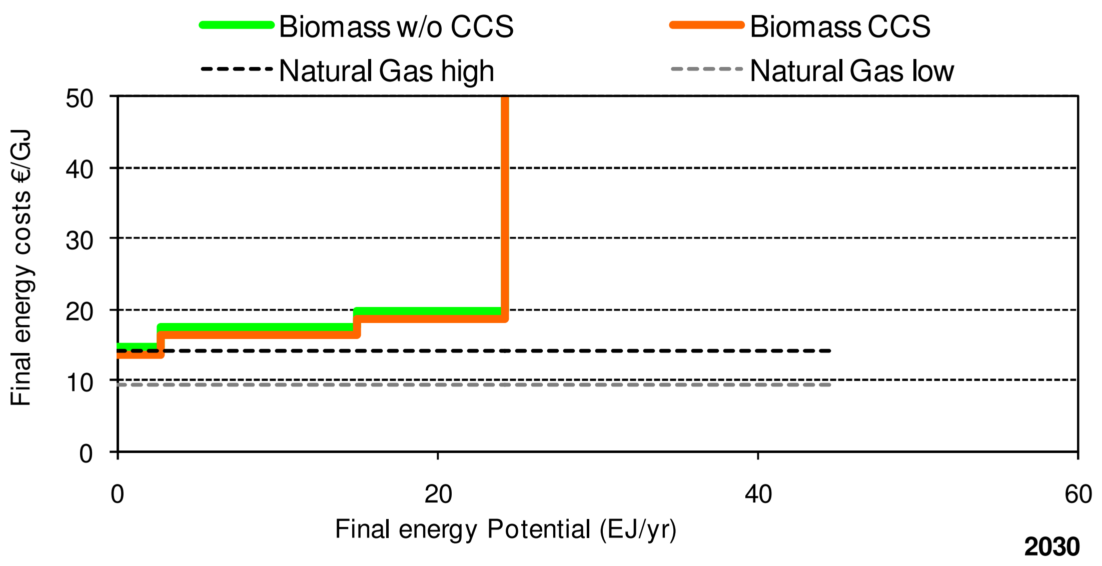
To obtain the total production costs for the different technology routes, we aggregate the conversion costs (including investment and O&M), fuel costs and CO_2 transport and storage costs. We also integrate the CO_2 price. This total production cost is compared to reference natural gas prices to estimate the economic potential.

3.4 Results for the economic potential

Below, we present the results for the economic potential for the biomethane routes. We present cost supply curves for biomethane production with and without CCS for the years 2030 and 2050, including low and high estimates for natural gas price as reference. All supply curves are based on a CO_2 price of 50 euro/tonne. In section 5, we show the effect of different CO_2 prices, and other variables, on the economic potential.

3.4.1 Gasification based biomethane

The supply curve for the gasification route is shown in Figure 3-1. The point where the supply curve crosses a natural gas price reference indicates the economic potential. The graphs shows that biomethane with CCS is more cost-effective than biomethane without CCS. This is explained by the relatively low incremental costs to apply CCS on biomethane producing installations and the relative high CO_2 price of 50 €/tonne. If we compare the costs of biomethane with natural gas, we see that there is only an economic potential under the 'high' gas price scenario (i.e. natural gas price of 14.2 €/GJ). In this 'high' gas price scenario the economic potential is 2.7 EJ (2030) and 4.8 EJ (2050).



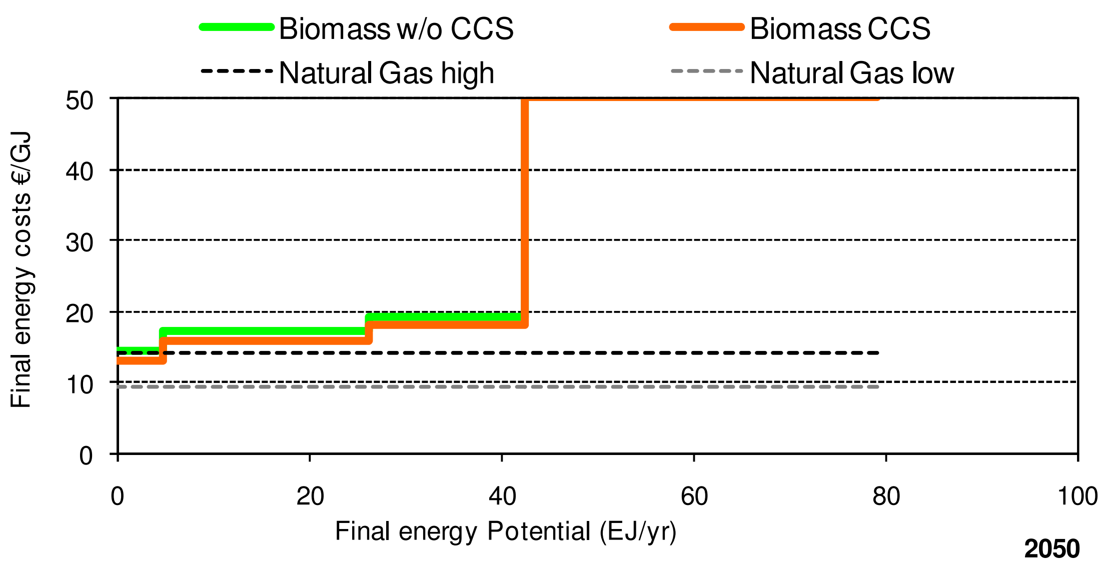


Figure 3 - 1 Supply curve for the **gasification-CCS route** in 2030 and 2050. Y-axis shows the cost of biomethane production (in €/GJ). X-axis shows the potential in final energy production (in EJ/yr).

3.4.2 Anaerobic digestion of energy crops and agricultural residues

The supply curve and with it the economic potential of the anaerobic digestion route is shown in Figure 3-2. The production costs of biomethane using digestion of energy crops and agricultural residues with CCS are lower than the same technology without CCS. Under the 'high' natural gas price scenario the economic potential is estimated at 1.4 EJ/y in 2030 and 2.4 EJ/yr in 2050. With only a moderate cost decrease (or moderate natural price increase above 15 €/GJ) the economic potential may increase significantly to 15 EJ/yr by 2050.

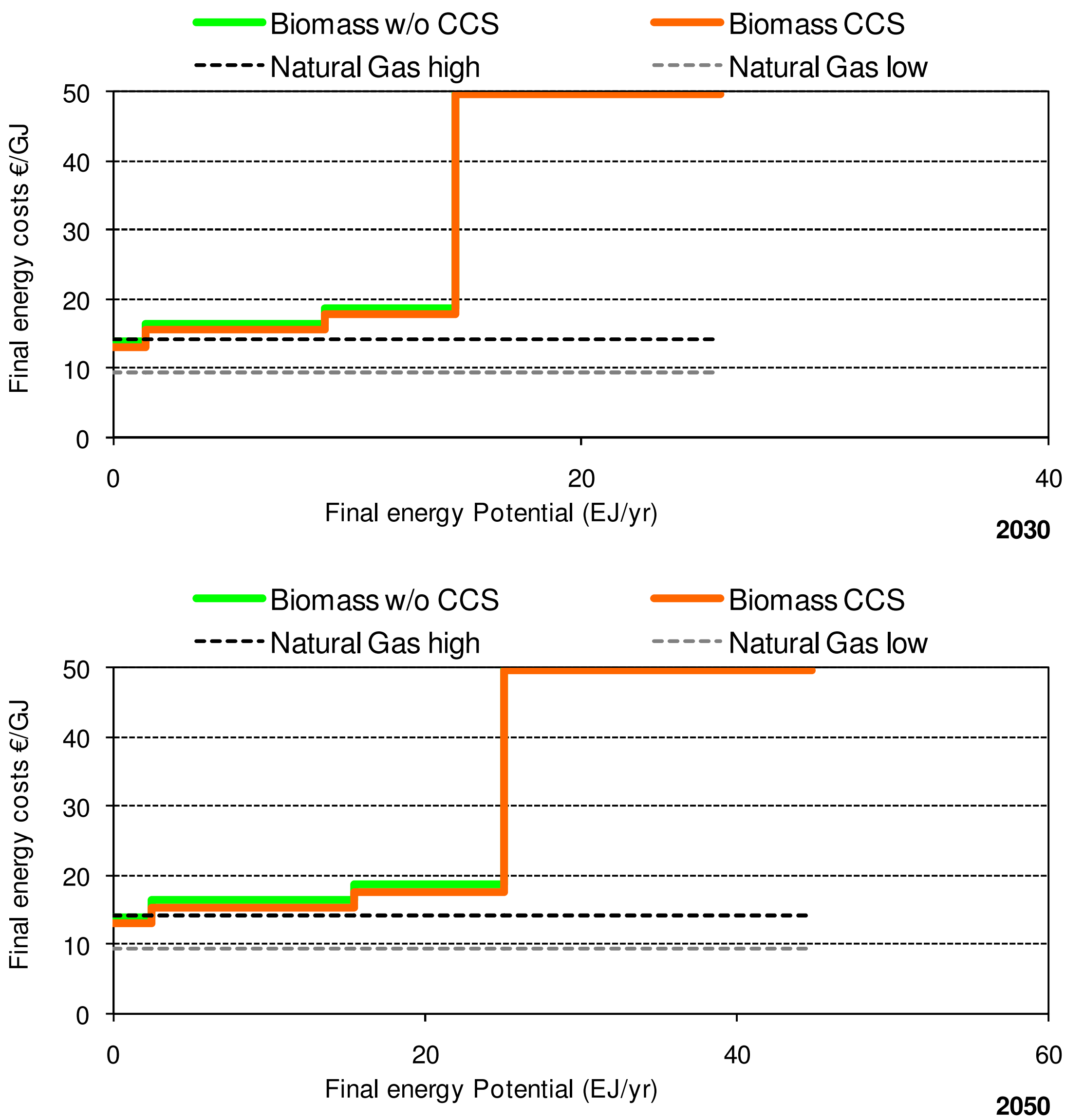


Figure 3 - 2 Supply curve for the **anaerobic digestion of energy crops and agricultural residues** in 2030 and 2050. Y-axis shows the cost of biomethane production (in €/GJ-biomethane). X-axis shows the potential in final energy production (in EJ/yr).

3.4.3 Anaerobic digestion of biogenic municipal solid waste (MSW)

The supply curve of the anaerobic digestion (MSW) route is shown in Figure 3-3. The graphs show that the full MSW potential (3.1 – 6.4 EJ) will be economically viable under the 'high' natural gas price scenario. A natural gas price higher than 11.3 €/GJ will make the potential economically viable in 2050. It is important to note that we assume that an infrastructure for gathering and distributing MSW is already present and these infrastructure costs are not allocated to the biomethane production costs.

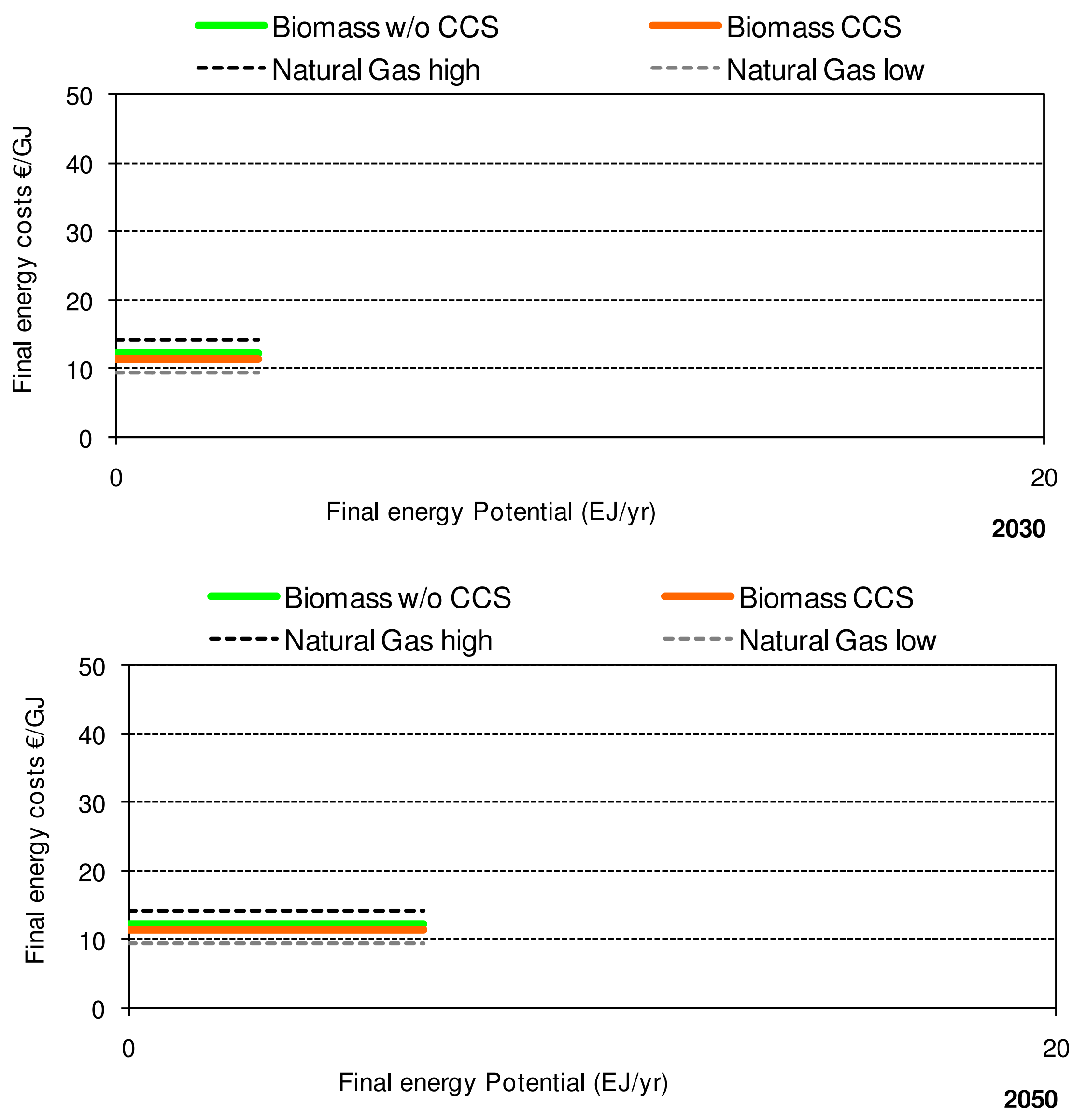
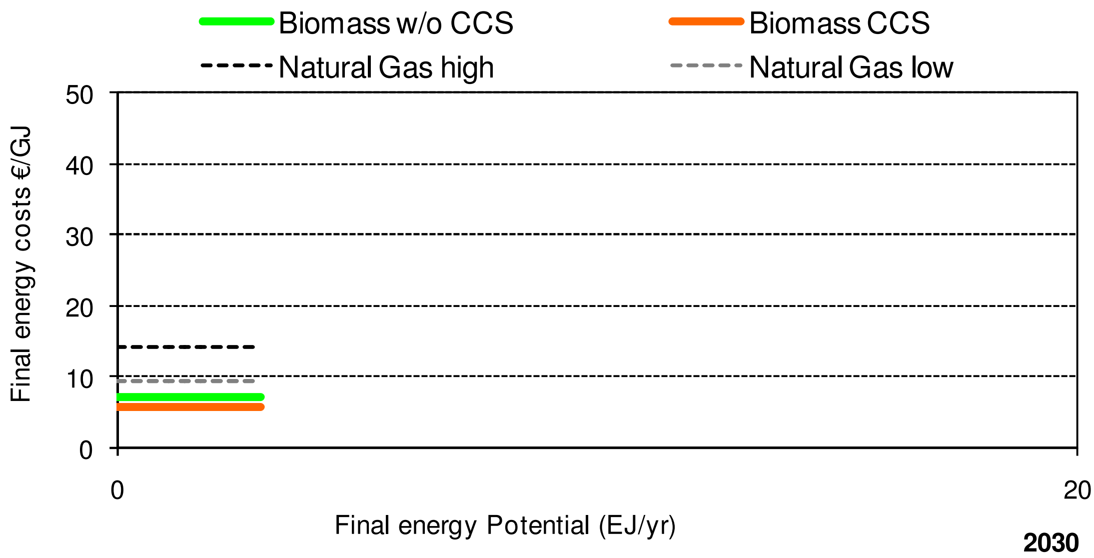


Figure 3 - 3 Supply curve for the **anaerobic digestion of MSW** in 2030 and 2050. Y-axis shows the cost of biomethane production (in €/GJ-biomethane). X-axis shows the potential in final energy production (in EJ/yr).

3.4.4 Anaerobic digestion of animal manure and sewage sludge

The supply curve and with it the economic potential of the anaerobic digestion of animal manure and sewage sludge route is shown in Figure 3-4. For manure and sewage sludge we also find a constant production cost as the potential increases. This is due to the assumption of zero feedstock cost, e.g. cost for the sewage infrastructure are not taken into account in the costs of biomethane production as this is assumed to be allocated to the treatment of animal manure and sewage sludge.

We see that biomethane from manure and sewage can be produced with the lowest costs compared to other biomethane production routes with CCS. The costs range from 5.5 to 5.8 €/GJ. This is significantly lower compared to the other investigated routes that have cost starting at 11.3 €/GJ_{final}. Even in the case natural gas prices are equal to values in our low natural gas price scenario (9.5 €/GJ), biomethane production and CO_2 removal from sewage sludge and animal manure can still be produced economically, certainly when assuming a CO_2 price of 50€/tonne. The overall result is that the economic potential for this technology route is equal to the technical potential, reaching 5.5 EJ by 2050.



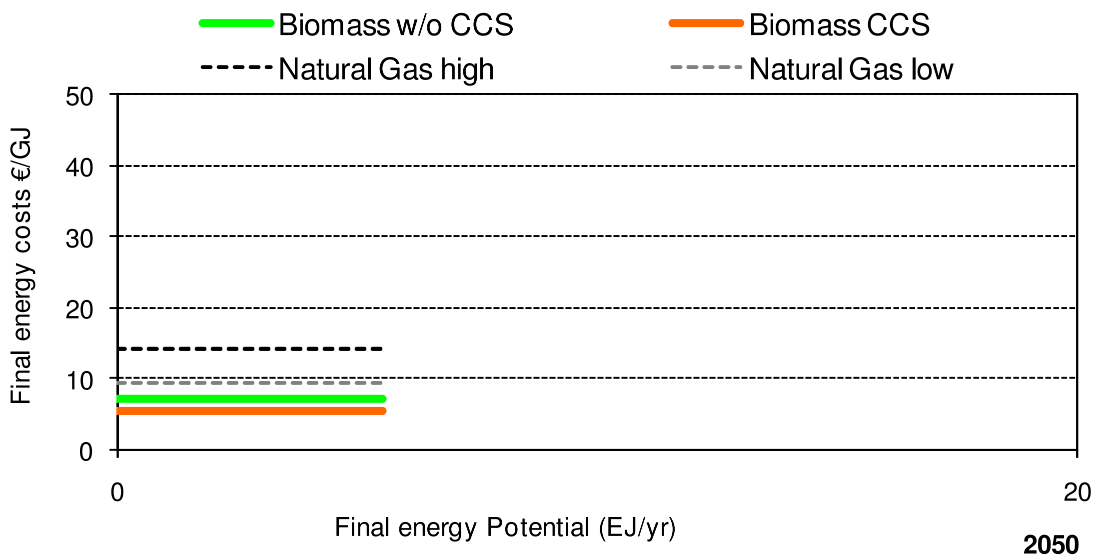


Figure 3 - 4 Supply curve for the **anaerobic digestion of animal manure and sewage sludge** in 2030 and 2050. Y-axis shows the cost of biomethane production (in €/GJ-biomethane). X-axis shows the potential in final energy production (in EJ/yr).

4 Market drivers and barriers

In this chapter, we present the key drivers and obstacles for the deployment of the biomethane-CCS technology routes.

In the previous chapter we estimated the economic potential of the various biomethane production technologies. How much of this economic potential is or can be taken up by the market is referred to as market potential. The market potential takes next to the economics also into account factors as market obstacles, logistics, public acceptance, political and regulatory constraints and policy support. In (IEA GHG 2011), the most relevant factors have already been identified for BE-CCS technologies in general. In this chapter we focus on the barriers and drivers specifically for the biomethane-CCS technology routes.

Feedstock quality limitations

Not all biomass is suitable for digestion (IEA Bioenergy 2011). Especially biomass containing significant amounts of cellulosic fibres (wood) should not be used in the digester, as they degrade slowly. Also, the remainders could form scum and block pumps, pipes or even the mixing equipment of the digester. Types of biomass that are typically highly contaminated (with sand or soil) can cause problems because solid deposits accumulate on the bottom of digester vessels and block pipes and pumps. Grass silage could be used, but only if processed to a small particle size. Grass has the tendency to float and unprocessed there is a fair chance that it will be collected on the liquor surface. It is therefore important to pre-treat the biomass before using certain feedstock. Pre-treatment measures that are commonly used include chopping, homogenisation, mixing and sand removal.

Limited plant capacity

Digester plant capacity is limited by two main reasons: the applied conversion technology does not allow large tanks and the high transport costs, which limits the availability of the feedstock. Transport costs are high because of the low energy density of the wet feedstock. This implies that most digesters are located near the biomass that is used in digester, such as farms. The maximum capacity of such digesters is about 15 MW. Plants processing solely sewage and manure are much smaller and the typical size limit is less than 1 MW. The capacity could be extended by the input of co-digestion material like organic residues or energy crops.

Gasification plants can be much larger, because transportation costs are less of an issue and the technology is more suitable to scale-up. On the longer term it may be possible to scale-up gasifiers to the GW size range. Nevertheless, the maximum size will depend on the location and the accessibility of the plant for the various required feedstock. Transportation costs can be reduced by increasing the energy density of the feedstock. There are densification processes available like torrefaction, but such processes are energy consuming and require additional investments (Meijden 2010).

Low natural gas prices and large trade capabilities

Biomethane competes directly with natural gas on the market. The high proven resources of natural gas and development of new extraction technologies for instance for shale gas production will enlarge the supply and will have a suppressing effect on the natural gas price. Also the increased trade capabilities for natural gas – e.g. in the form of increasing number of LNG terminals and long distance gas pipelines like the Nordstream pipeline between Russia and Europe – will have a suppressing price effect. As international trade of gas is expected to grow between regions (see (IEA 2010), this has most likely a negative impact on the economic potential of biomethane and with it on the potential of biomethane with CCS.

Decentralised biomethane options in combination with CCS

The implementation of decentralised production of biomethane and end-use, in combination with CCS is deemed unlikely. CO_2 removal from digestion based biogas is only needed when the biomethane is to be injected in the natural gas grid. Upgrading is not needed when the biogas is used locally in for instance in small combined heat and power installations or in heating systems. The situation of higher CCS costs combined with smaller production units (diseconomies of scale) will increase substantially the costs of CO_2 capture, transport and storage.

Biogas injection in existing gas infrastructure

Injection of the produced biomethane into the existing gas infrastructure is technically possible, but requires special attention. Some considerations depend on whether the gas is injected into the high pressure transport grid or the low to medium pressure distribution grid.

Injection in the low to medium pressure distribution grid

An advantage of injecting the produced biomethane in a *regional* distribution network is the relative low operating pressure – about 7 bars - of this network, reducing the energy and investment requirement for biomethane compression facility. The injection capacity, however, may be limited by the demand. In certain situations, seasonal natural gas demand (e.g. in the summer) may be very low. This requires fine-tuning in the supply and capacity of the biomethane installations that are connected to the regional gas grids. Preferably, injection should take place as much upstream as possible. To control the costs for biomethane transportation, the location of the biomethane production must also be near the injection point into the natural gas grid.

Injection in the high pressure grid

It is also possible to inject the biomethane into the (national) transportation grid, which requires pressurising the biomethane to 40 – 70 bars, which will add to the costs of the biomethane. The biomethane production facility should in this case preferably be close to the injection point of the natural gas transport grid, to avoid the need of long feed pipelines and capacity should as high as possible to achieve economies of scale. Furthermore, the number of injection points is limited and feeding into the grid requires good alignment with the grid operators.

Security of supply

Future scenarios estimate that Western Europe and Asia will become more and more dependent on other regions for their natural gas supply (IEA 2011). Production of biomethane can, among others, reduce the import dependency, and, consequently, the negative geopolitical impacts. Asia has in this respect the best prospective as the technical biomethane potential would allow to cover about 50% of the total demand in 2050, where this is more in the range of 20% for Western Europe.

Biofuel targets EU

One of the drivers for the development of biomethane installations are the European targets on biofuels in transportation (Meijden 2010). Biofuels can be produced in various ways and currently the European Commission (EC) distinguishes two types of biofuels: first and second generation. Biofuels produced from glucose based biomass (e.g. corn, wheat and rape seed) are seen as first generation biofuels, where biofuels produced from non-food cellulosic material (e.g. wood) are indicated as second generation biofuels (Meijden 2010). Biomethane can thus be regarded a second generation biofuel under certain conditions. The EC has proposed to double count second generation biofuels when replacing fossil fuels to achieve the European targets. This accounting method would give 'second generation' biomethane a significant advantage over first generation biofuels.

Unique feedstock-technology match

Some biomass feedstock and biomethane production technology form a unique combination, and may have important co-benefits. An example is anaerobic sludge digestion from municipal waste water treatment. This reduces the costs of treatment and is considered an essential part of a modern treatment facility. It further reduces sludge disposal, and exposure to pathogens and odour. This is clearly a very important driver for the deployment of biomethane production from sewage sludge. The removal of CO_2 is needed when the biomethane is to be injected in a natural gas grid. Drivers for the deployment of biomethane combined with CO_2 capture are then possible locations where industrial demand for captured CO_2 is present. Areas of interest would be near large cities or metropolises or near industrialized areas.

Another example of a strong feedstock-technology match is the possibility to use hydro cultured biomass like algae in combination with digestion. The high water content makes this biomass feedstock attractive for this route.

End-use and existing infrastructure

Biomethane production and injection into the natural gas infrastructure can make optimal use of the existing infrastructure for gas transport and end-use. No adaptations are required by the end-users of (natural) gas which eases the adoption of this option in the energy mix.

Biogas collection network with centralised upgrading and injection of biomethane

Stimulating biogas (!) collection networks could be a driver for digestion-CCS. Typical elements in a biogas network with CCS would be: biogas production, compressor (for biogas transport), biogas pipeline, collect and treatment/upgrading plant, pipeline to feed-in natural gas plus compressor, CO_2 compressor (plus purification step if needed), and CO_2 pipeline to feed-in CO_2 into the CO_2 grid.

The optimal configuration of a biogas network is not easy to determine and will strongly depend on local conditions, including: land-use (urbanized areas will have higher transport cost), grid specifications (pressure and purity requirements) for natural gas and CO_2, transport distance and annual flows of available biomass, and the distance to the natural gas (and possibly CO_2) grid.

It is outside the scope of this study to assess the cost of clustered biomethane production in combination with CCS and further research may prove to be valuable to better understand how all these variables interact and influence the cost. We do however briefly discuss the possible effects of economies of scale that might be achieved in such networks.

IEA (2009) states that upgrading costs for anaerobic digestion are dependent on the technology (PSA, water, or amine scrubbing), but most importantly on the size of the plant. For a flow rate above 500 Nm³/h (~2.5 $MW_{biomethane}$), biogas upgrading processes have costs at about 1.2 - 1.8 ct/kWh_{biogas}. Upgrading of lower volume flow rates is much more expensive (up to 2.5 ct/kWh_{biogas}); and more depending on the process used. As a rule of thumb, the specific investment cost increase by a factor 2 when scaling up from a 250 Nm³/h to a 1000 Nm³/h amine based CO_2 removal facility (factor 4 size increase). Economies of scale are thus of high importance. For reference, this translates into specific treatment cost (including O&M and energy cost) of approximately 6 Euro/$GJ_{biomethane}$ (250 Nm³/h) and 4 Euro/$GJ_{biomethane}$ (1000 Nm³/h).

For feed-in to the national gas grid economies of scale also apply to the transport infrastructure (from biogas digester to the national gas grid), equipment needed at the injection point and the compressors to allow grid injection (both CO_2 as natural gas grid). Economies of scale certainly also apply to the CO_2 infrastructure (compressors and pipelines). To take optimal advantage of economies of scale it is thus possibly of interest to collect the biogas from multiple digesters and upgrade this to biomethane in a single upgrading plant. Again, local situation will be strongly influencing the cost and more research is needed to draw final conclusions.

5 Sensitivity analysis

In this chapter, we present the results of the sensitivity analysis. The sensitivity analysis is used to assess the effect of uncertainties on the outcomes presented in the preceding chapters. In a sensitivity analysis one parameter/assumption in the model is varied and the effect on the outcomes of the model is reported. We selected important parameters/assumptions based on the expected uncertainty of input data and on the overview of drivers and obstacles for the biomethane-CCS routes as presented in chapter 4. Each variable is assessed separately and the relative or absolute change compared to the base case results for the technical and economic potential are reported.

5.1 Summary

We selected several variables for the sensitivity analysis, being: CO_2 price, natural gas price, biomass price, discount rate, cost of CO_2 transport and storage, sustainability criteria for biomass supply, CO_2 storage capacity estimates and exclusion of possible storage reservoirs.

The results show that the economic potential is highly dependent on the **CO_2 price**. At 20 €/tonne CO_2 there is only an economic potential for digesting MSW and sewage sludge and manure in combination with CCS. With a price of 100 €/tonne CO_2 the potential increases to a maximum of 43 EJ/yr.

The **natural gas price** directly affects the economic potential and is the most important determinant of the economic potential. If the gas prices reach 14.2 €/GJ the economic potential can be up to 14.3 EJ/yr, while, leaving other variables unchanged, the economic potential more than halves if the gas prices drop to 9.5 €/GJ.

The **biomass price** affects the production cost of all routes. Halving the biomass price results in a decrease in production costs up to 21%.

The effect of a higher or lower **discount rate** is typically more severe for the (relatively) capital intensive routes, such as the anaerobic digestion of MSW, sewage sludge and animal manure. At higher discount rates (15%), the maximum economic potential of gasification evaporates. At low discount rates (6%) the maximum economic potential of anaerobic digestion of energy crops and agricultural waste increases to over 15 EJ/yr by 2050 and the total economic potential for the digestion-CCS route doubles.

Doubling the **costs of CO_2 transport or storage** leads to an increase in the production cost of maximally 10%. When the costs are halved, the production costs will decrease up to 5%. However, there is no impact on the economic potential if these changes are applied.

The technical and economic potential are not influenced by using lower or higher estimates for the **global storage potential**, as this is not the limiting factor in the global regions.

Finally, the analysis shows that potential estimates are highly dependent on estimates for the **sustainable biomass potential**.

5.2 Variables selected for analysis and base case results

We selected important parameters/assumptions based on the expected uncertainty of input data and on the overview of drivers and obstacles for biomethane-CCS routes as presented in chapter 4. This yields the list of variables presented in Table 5 – 1.
The impact of the natural gas prices is shown in each sensitivity analysis: Where relevant, we show the minimum economic potential, at high prices of €14.2/GJ and the maximum economic potential, at low prices of €9.5/GJ.

Table 5 - 1 Ranges used for key assumptions in the sensitivity analysis. Note that each variable is assessed separately

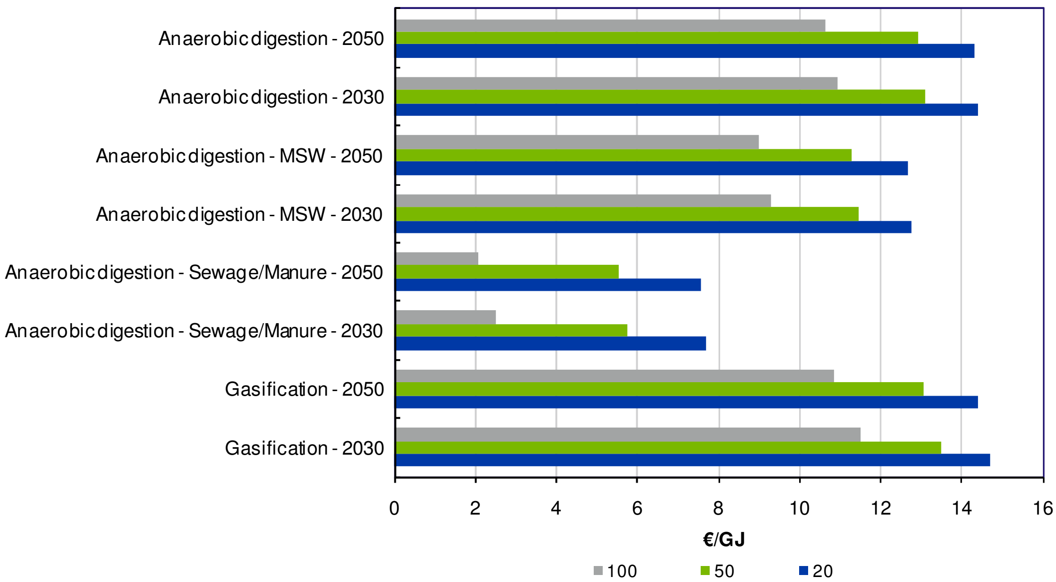
Variable	Unit	Base case	Variant 1	Variant 2
CO_2 price	€/tonne	50	20	100
Biomass price	%	100%	-50%	+50%
Discount rate (cost of financing)	%	10	6	15
Cost of transport	€/tonne	5	3	10
Cost of storage	€/tonne	5	1	13
Sustainability criteria biomass supply	-	Strict	Mild	No
Storage capacity estimates	-	Best	Low	High
Annualised storage capacity factor	Years	50	70	
-CO_2 storage reservoirs -inter-regional transport of biomass and CO_2	-	-all reservoirs -inter-regional transport included	-hydrocarbon reservoirs only -inter-regional transport excluded	

5.3 Results of the sensitivity analysis

5.3.1 CO_2 price

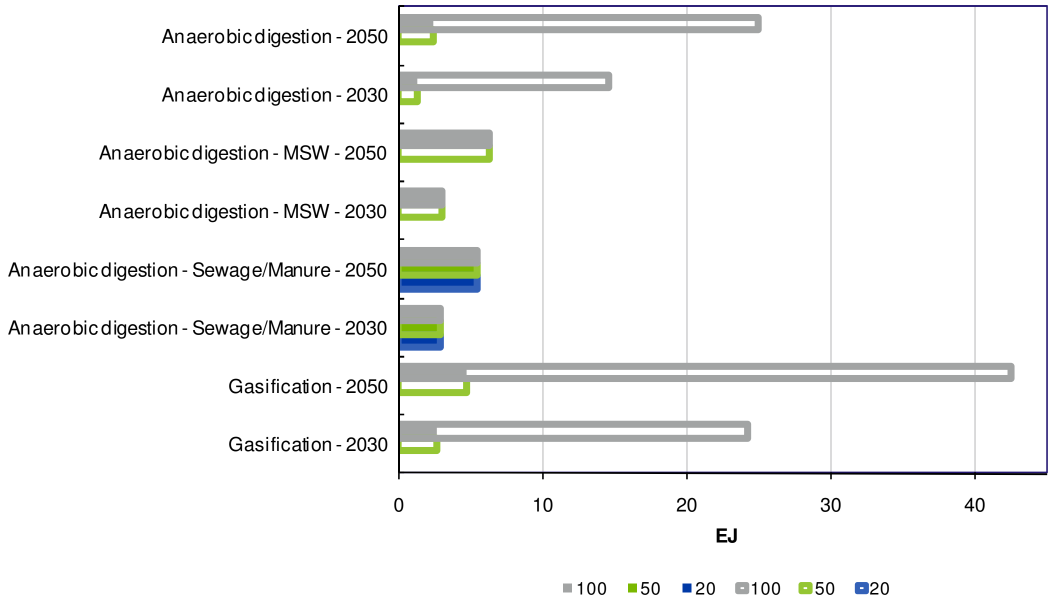
CO_2 prices have a large impact on the costs of biomethane production and natural gas consumption (via carbon pricing), impacting the economic potential of the different routes. At a price of 20 €/tonne[17], the production costs of gasification increases up to 10% (compared to a situation with a CO_2 price of 50 €/tonne), of anaerobic digestion the costs increases between 10% and 37%. At a CO_2 price of 100 €/tonne, the production costs of gasification decreases up to 17%, for anaerobic digestion the cost decreases between 16% and 62%.

Consequently, the maximum economic potential for gasification and anaerobic digestion shrinks to zero at lower CO_2 prices, but increases to 43 EJ, respectively 37 EJ in 2050 under high CO_2 prices.



(a)

[17] In November 2011, the EUA prices dropped below € 10/tonne.



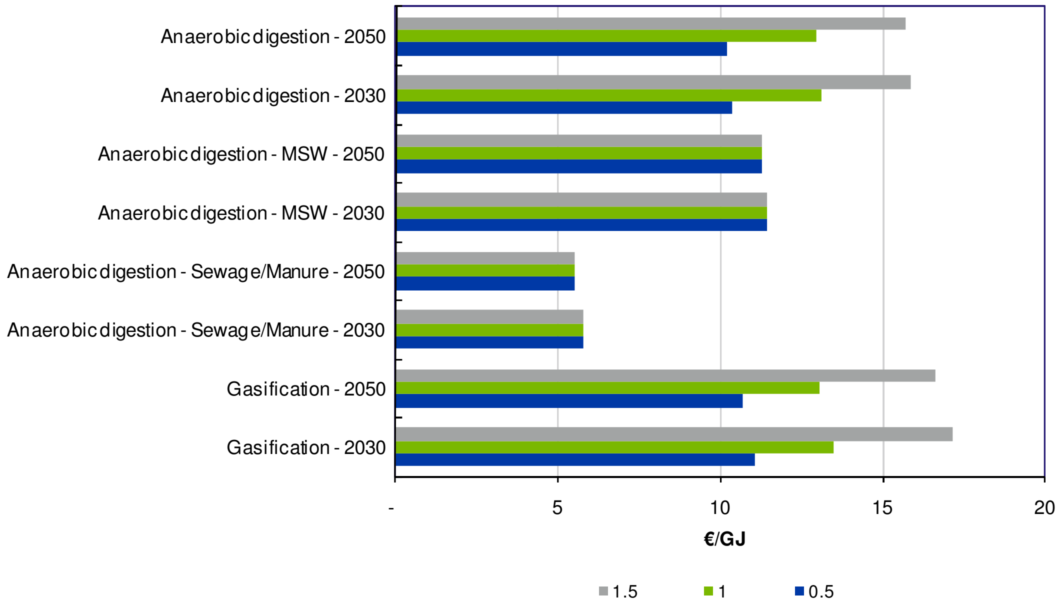
(b)

Figure 5 - 1 Impact of CO_2 price on production cost (a) and economic potential (b) in 2030/2050. The solid bars in (b) indicate the minimum economic potentials; the outlined bars indicate the maximum economic potentials.

5.3.2 Biomass price

The biomethane production cost for anaerobic digestion of MSW and sewage sludge/animal manure are not affected by a doubling or halving of the biomass price, as feedstock cost are assumed to be zero. The production cost of gasification (anaerobic digestion) decreases up to 18% (21%) if the biomass price decreases with 50% and increases with 27% (21%) if the biomass price increases with 50%.

The minimum economic potential is not impacted by a decrease or increase of 50% of the biomass price. The maximum economic potential increases at low biomass prices to 37 EJ for anaerobic digestion and 42 EJ for gasification in 2050. At high biomass prices for residues and energy crops, there is no economic potential for both routes.



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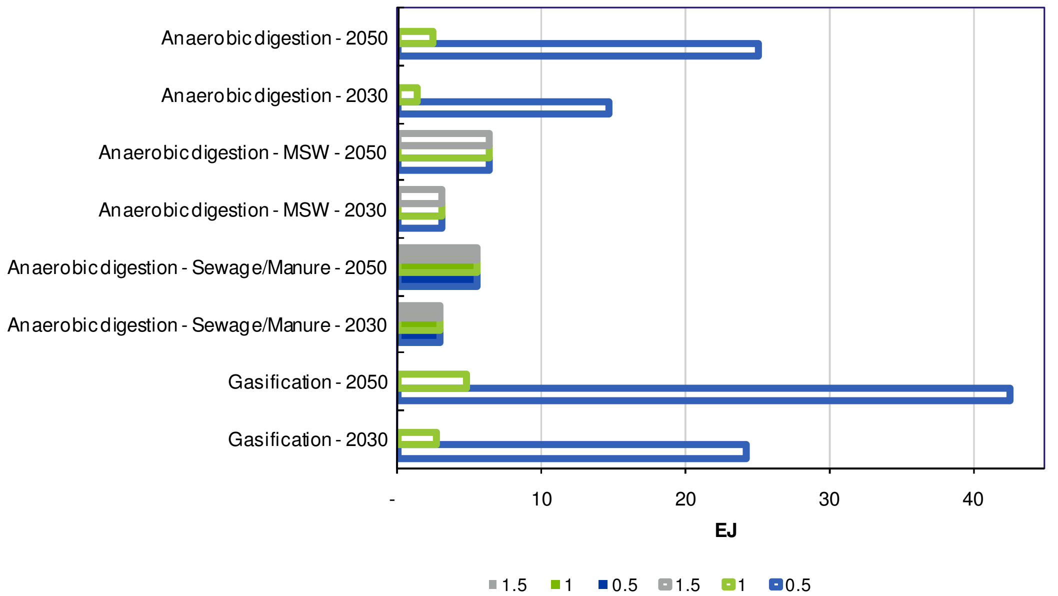


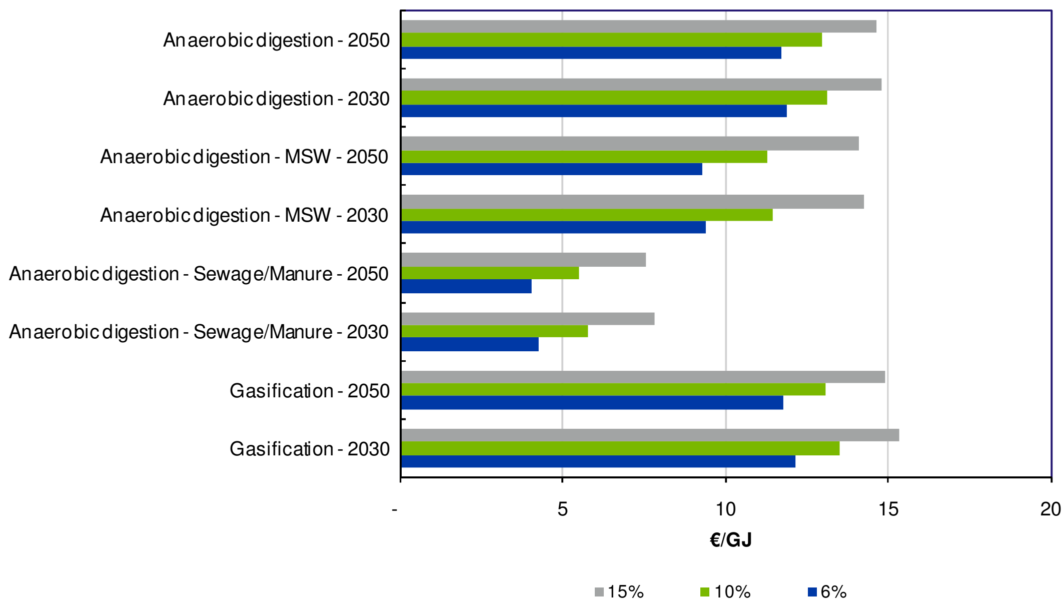
(b)

Figure 5 - 2 Impact of the biomass prices on production cost (a) and economic potential (b) in 2030/2050. The solid bars in (b) indicate the minimum economic potentials; the outlined bars indicate the maximum economic potentials. 0.5, 1 and 1.5 are the multiplication factors that were applied to the biomass price.

5.3.3 Discount rate

The default value of the discount rate is 10%. If this increases to 15%, the production costs increase substantially: 14% for gasification and 13 to 37% for anaerobic digestion. Especially the results for digestion of sewage sludge/animal manure and MSW are sensitive to changes in the discount rates as capital costs have a high share in the production costs. The other way around, decreasing the discount rate to 6%, decreases the production costs for gasification by 10%. For anaerobic digestion, the decrease ranges between 9% and 27%.

The variation of the discount rate does only impact the economic potential of anaerobic digestion of MSW in the case of high natural gas prices: At a discount rate of 6%, the economic potential increases from 0 to 6.4 EJ in 2050. For gasification, the economic potential evaporates at discount rates of 15%. At low discount rates, the maximum economic potential of anaerobic digestion of energy crops and agricultural residues increases to over 15 EJ.



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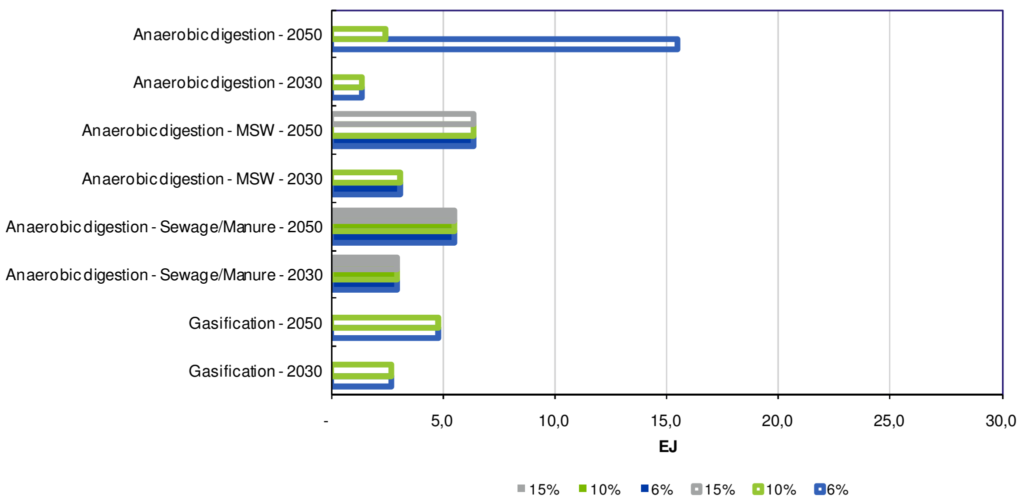
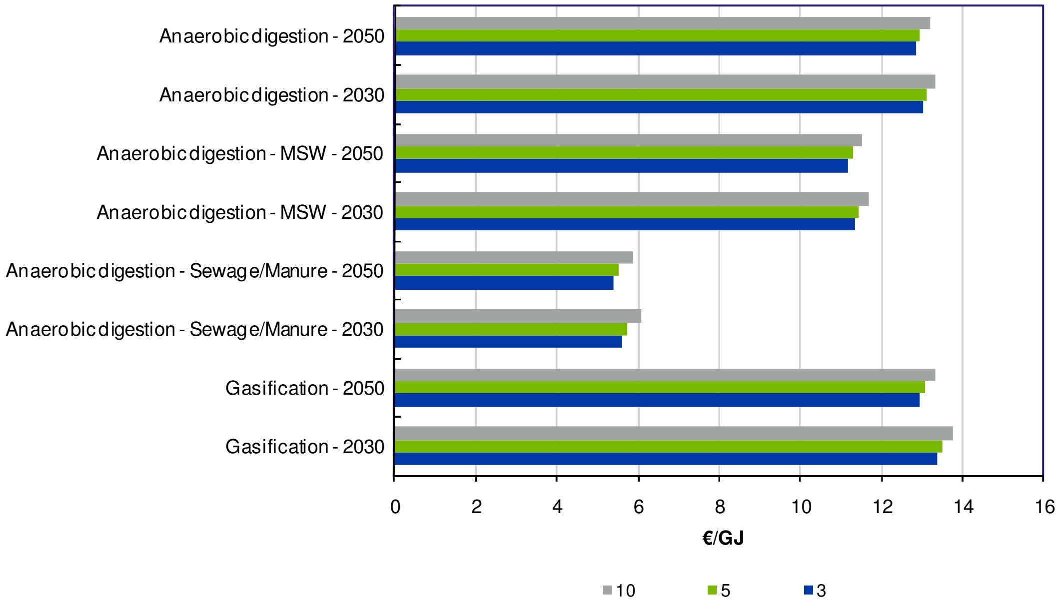


(b)

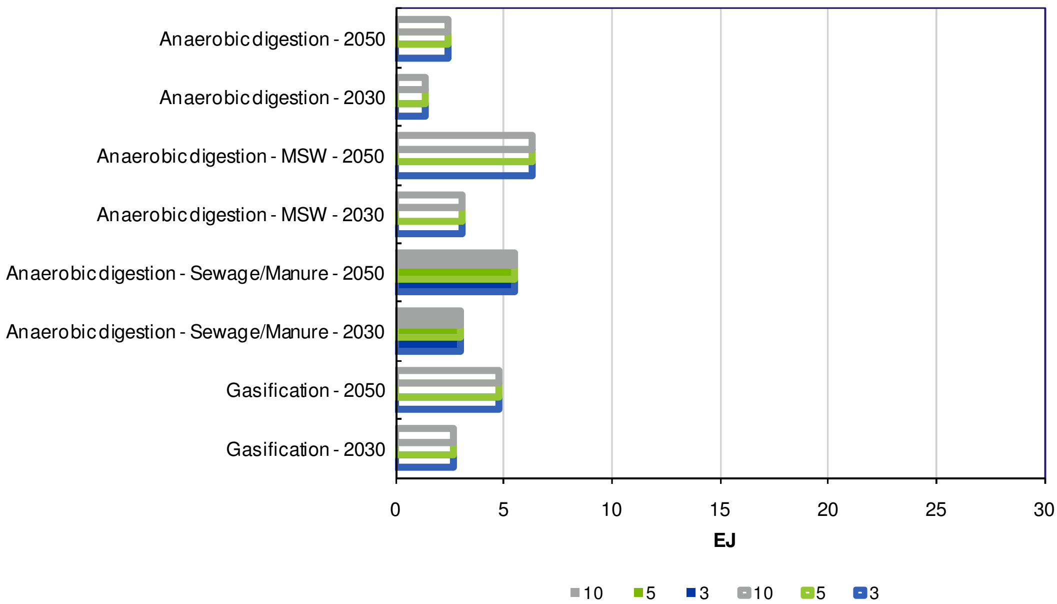
Figure 5 - 3 Impact of discount rates on production cost (a) and economic potential (b) in 2030/2050. The solid bars in (b) indicate the minimum economic potentials, the outlined bars indicate the maximum economic potentials.

5.3.4 Cost of CO_2 transport and storage

The cost of final energy production and the economic potential are influenced by CO_2 transport and storage cost. This is shown in Figure 5-4 and Figure 5-5. Because only a small fraction of the carbon content of the feedstock is finally captured as CO_2, the impact of changes in transport and storage costs is marginal. For all but anaerobic digestion of sewage/manure the production costs only changes up to 3% if the transport or storage costs are increased, respectively decreased to the high, respectively low values. Only for anaerobic digestion of sewage/manure the impact is relatively high, up to 10%, mainly due to the relatively low production costs. Changes in production costs due to higher or lower transport and storage cost do not have an impact on the economic potential.

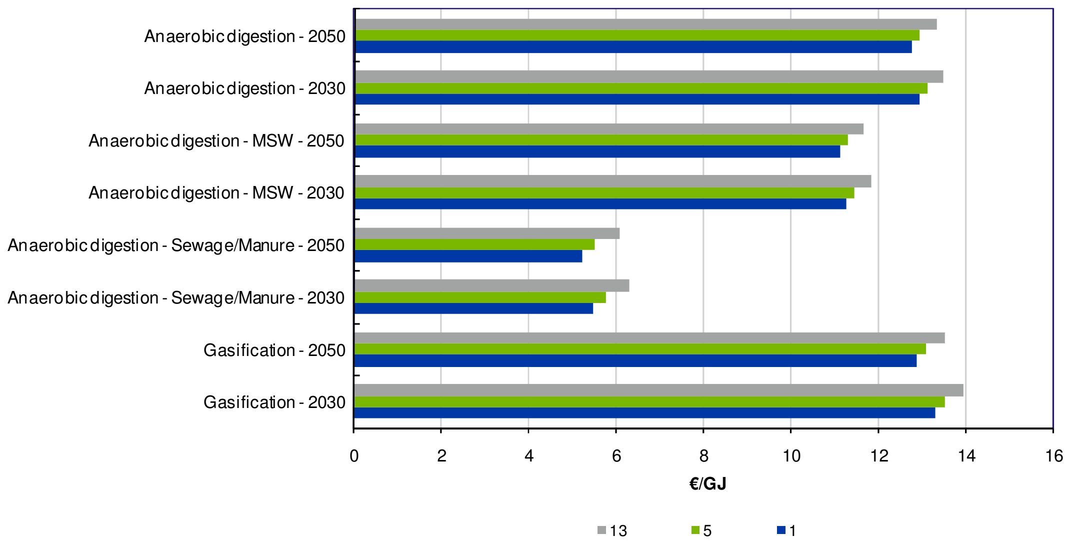


(a)

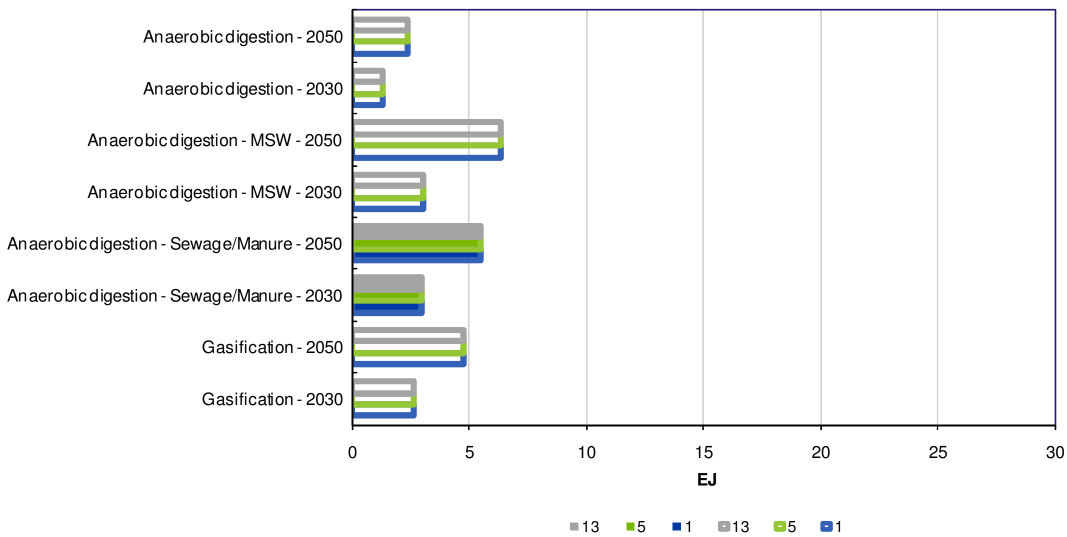


(b)

Figure 5 - 4 Impact of CO_2 storage cost (€3, €5 or €10 per tonne) on production cost (a) and economic potential (b) in 2030/2050. The solid bars in (b) indicate the minimum economic potentials; the outlined bars indicate the maximum economic potentials.



(a)



(b)

Figure 5 - 5 Impact of CO_2 transport cost (€1, €5 or €13 per tonne) on production cost (a) and economic potential (b) in 2030/2050. The solid bars in (b) indicate the minimum economic potentials; the outlined bars indicate the maximum economic potentials.

5.3.5 Sustainability criteria for biomass supply

For MSW and sewage sludge/animal manure there are no estimates available for the technical biomass potential under different sustainability criteria. As a result, the technical potential is not affected by varying these criteria. For the other feedstock types (forestry residues, agricultural residues and energy crops), applying criteria has a substantial impact. Without criteria (default set at 'strict'), the final energy and net negative emission potential for gasification would be 66% higher in 2050 and for anaerobic digestion, the potential would be 78% higher in 2050.

This analysis shows that potential estimates are highly dependent on estimates for the sustainable biomass potential. By no means should the results of this sensitivity analysis be interpreted as an argument to omit sustainability criteria or to apply mild sustainability criteria to increase the biomass potential.

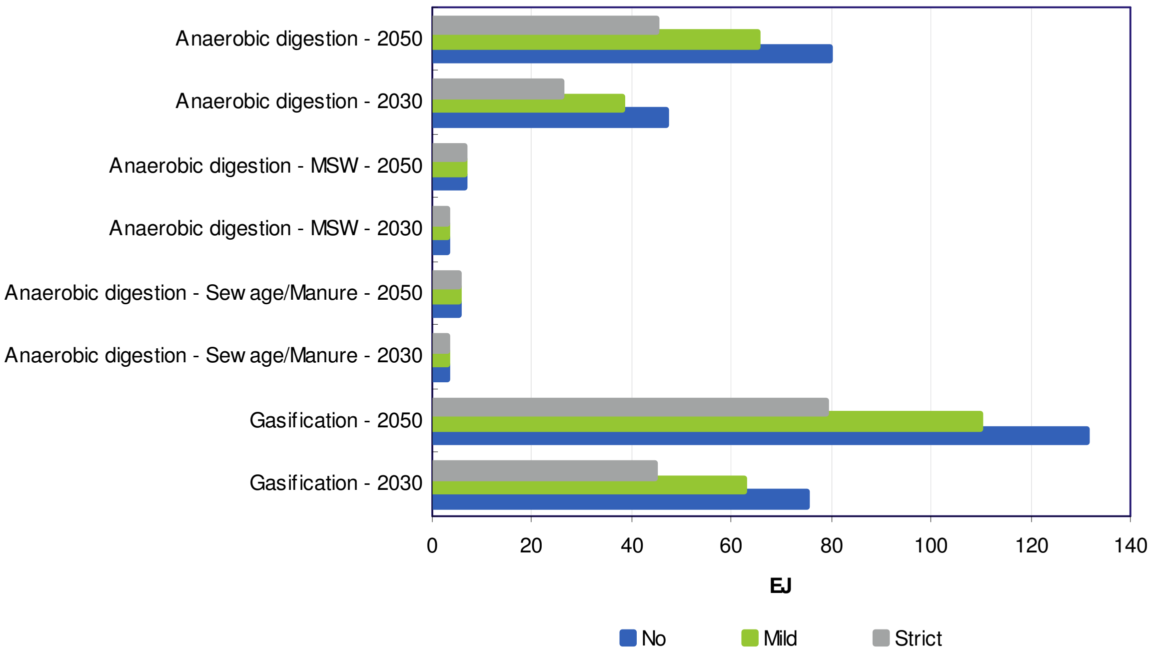


Figure 5 - 6 Impact of sustainability criteria (No, mild or strict) on the technical potential in 2030/2050 in annually produced final energy.

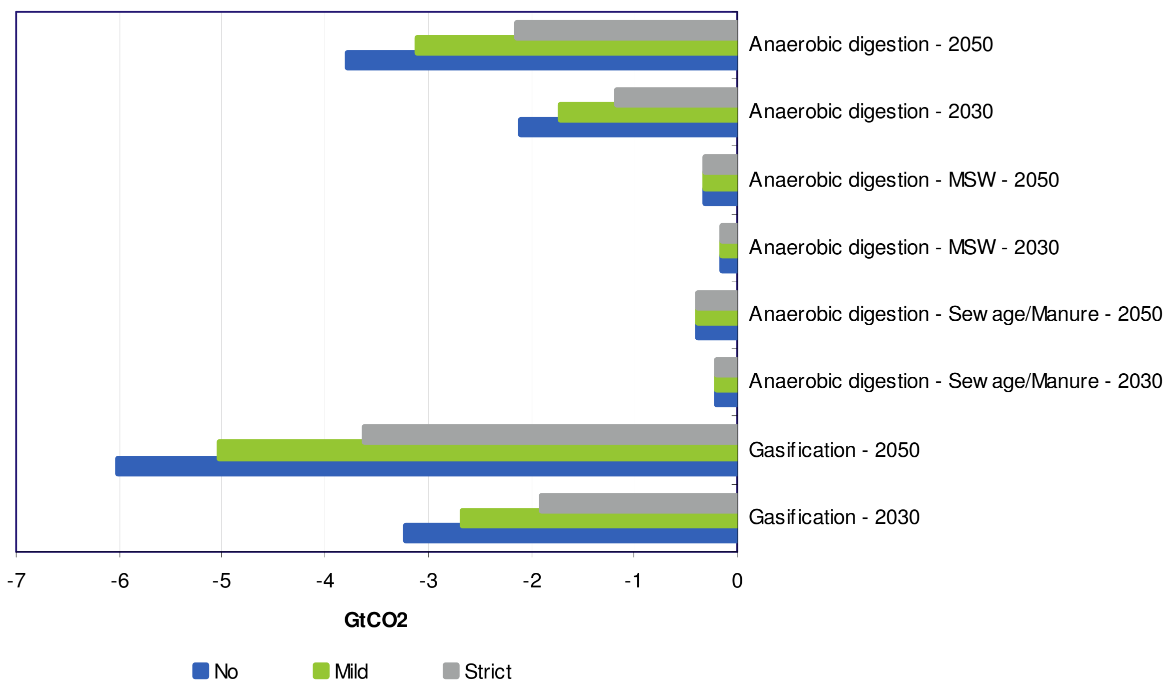


Figure 5 - 7 Impact of sustainability criteria (No, mild or strict) on the technical potential in 2030/2050 in terms of negative emissions that can be realised per year.

6 Discussion

In this chapter, we summarise the results of the study and compare our results with those from other studies. We also discuss the impact of different assumptions on our results and highlight knowledge gaps and uncertainties that influence the outcomes.

6.1 Comparison to earlier studies

We are not aware of studies assessing the global potential for biomethane production in combination with CCS, so it is not actually possible to compare the results of this study in that respect. We can however compare the results with potential estimates for biomethane without CCS to place our results in perspective. Especially since storage capacity is not likely to become a limiting factor for the technical potential for biomethane with CCS.

Potential studies for biomethane are quoted in (NGVA 2010)[18]. There a German study is quoted estimating that anaerobic digestion and gasification routes may produce 7-12 EJ from residual products and sustainable energy crops. The area of research is the vicinity of the European gas grid (EU-28). Their estimate including CIS (Commonwealth of Independent States) countries ranges between 14 and 21 EJ. Another estimate for the EU-27 region quoted in NVGA reports 1.6 EJ of biomethane that could come from waste streams, including manure and waste water sludge. "Estimations on the biogas potential of energy crops from anaerobic digestion in EU-27 show yields ranging between 0,9 to 2,7EJ" (NGVA 2010). These estimates can best be compared to the technical potential for OECD countries in the EU (OEU) in our study. The potential estimates in our study range between 2.2 and 3.6 EJ for this region in the year 2030. This is thus a somewhat higher estimate but not out of order when compared with results presented earlier.

We also provide a comparison of the results found here with results for other BE-CCS routes as presented in (IEA GHG 2011). The technical potential estimates for biomethane production with CCS range between 57 and 79 EJ in 2050. The gasification-CCS route producing biomethane has a higher potential than the BE-CCS

[18] See for more details Nielsen, J. B. H. and P. Oleskowicz-Popiel (2008). The Future of Biogas in Europe: Visions and Targets until 2020. "Biogas - a promising renewable energy source for Europe" AEBIOM Workshop - European Parliament, Brussels.

routes producing electricity as reported in (IEA GHG 2011). There, the highest potential was estimated at almost 60 $EJ_{electricity}$ in the IGCC co-firing coal and biomass. The net negative emissions are however estimated to be higher for the gasification routes producing electricity: up to 10 Gt compared to up to 3.5 Gt of negative greenhouse gas emissions for the routes producing biomethane. The results for the biomethane routes suggest a higher technical potential compared to bio-ethanol and biodiesel production with CCS, although end-use conversion efficiency is not taken into account here. This is relevant when comparing the actual greenhouse gas emission savings that can be achieved.

Producing biomethane combined with CCS is economically attractive for about 14 EJ and under 1 Gt of negative GHG emissions. The economic potential for the earlier studied BE-CCS routes producing electricity is about 20 EJ at its maximum. The latter potential comes with negative emissions above 3 Gt CO_2 eq. The economic potential thus seems to be higher for the (gasification based) BE-CCS route producing electricity.

6.2 Limitations when estimating potentials

Technical potential

Factors affecting the overall assessment of technical potential of BE-CCS routes are discussed in detail in (IEA GHG 2011). Here we focus on the limitations that we encountered when assessing the technical potential for the biomethane-CCS routes.

Feedstock limitations

For the digestion route we assumed that 30% of the technical potential for energy crops and agricultural residues is not available for conversion; we exclude the full potential for forestry residues. This assumption has direct impact on the results for the technical potential in terms of final energy and negative emissions.

Van Vuuren assumes 100% woody biomass in their estimates for energy crops to prevent competition with food production. This woody biomass is assumed to be grown on abandoned agricultural land and natural grass lands. This would result in a very low to zero potential for the digestion route, which is not deemed likely. It is likely that non-woody species will be developed to grow in these areas providing a suitable and sustainable feedstock for the digestion route. We however want to take into account that not all feedstock are suitable to be converted in the digestion route resulting in the rather arbitrary 30% reduction of the biomass potential (for energy crops and agricultural residues) available for the digestion route.

Methane balance

In this study we excluded the possible impact of methane leakage or slip from conversion, capture and infrastructure components on the greenhouse gas balance. In the case of digesters, methane losses can occur in gas storage devices. It can also slip to off-gases from biogas upgrading processes, including the CO_2 stream from the

CO_2 removal step. The uncertainty of the estimates is high, but Murphy and Power (Murphy and Power 2009) quote 6% losses from digester and methane storage systems; and 1.5% losses from the biogas upgrading system, but methane losses vary per CO_2 removal technology (Appels, Baeyens et al. 2008; Murphy and Power 2009). (Appels, Baeyens et al. 2008) state that methane losses during biogas upgrading (i.e. CO_2 removal) have to be kept low as methane has an global warming potential that is 25 times higher than CO_2 and it obviously has negative impact on economics. We did not include methane slip into the greenhouse gas balance because at these sizes of biomethane plants we included in the study (10 – 15 MW) the economical and technical requirements for the process must be on a professional level and meet legal requirement on methane emission. Technically it is already possible to limit the methane emissions to a small amount (e.g. below 0.5 %) including the CO_2 removal process. But to indicate the impact of methane leakage: if we take the high leakage estimate of Murphy and Power (2009), the GHG emissions from leakage (considering the global warming potential of methane) can fully annul the negative GHG emission impact achieved by implementing CCS.

If MSW is not digested but composted instead, methane emissions will occur. In the case of an uncontrolled environment where all methane is released. The IPCC 2006 Guidelines for National Greenhouse Gas Inventories indicates that the average methane emission factor of MSW treatment with anaerobic digestion is five times lower than of composting.

Digestion is one option to dispose sewage sludge from municipal waste water plants. Other options, such as landfill, may have high methane and CO_2 emissions as consequence (cf (Houillon and Jolliet 2005)). Between 0 and 50% of the carbon content could be converted to methane in untreated sludge (in anaerobic digestion this is about 80%, IPCC, 2006). From a life cycle perspective digestion may thus also prevent GHG emissions as it substitutes other disposal options.

Anaerobic digestion is thus a good way to avoid methane emissions, but it is very important to minimise (downstream) losses.

Losses that are outside of our system boundary, but still of interest to bring to the attention are methane losses during transport in the (natural) gas infrastructure. For example, leakage rates for the Russian transmission system are reported to range between 0.36% and 3% (Papadopoulo, Kaddouh et al. 2009). Such infrastructure losses are not likely to significantly differ when natural gas will be replaced by biomethane. Typically European gas grids do have much lower methane losses than Russian grids. A substitution of imported gas (with high leakage rates and electricity consumption for compression/transport) by local biomethane will probably lower the leakage rates and has a positive effect on greenhouse gas balance.

The net effect on the greenhouse gas balance depends on the type of conversion and biogas upgrading system. It also depends on the (current) disposal options and whether biomethane production substitutes a GHG emitting disposal option, see for more information (EUCAR, CONCAWE et al. 2007; JRC 2008). It also depends on the region as (natural) gas leakage rates from infrastructure are not equal across all regions. These factors are outside the scope of this study but it is recommended to assess these aspects in more detail in future research efforts.

Economic potential

Cost development of conversion and CCS technologies

The cost development for conversion technologies with CCS is an important factor when determining the economic potential. Cost developments can be gradual or more abrupt when a radical new technology is brought to the market. We have been rather conservative in estimating cost reductions towards 2050 and did not include innovative conversion technologies such as supercritical water gasification (hydrothermal gasification). The main reason for this conservative approach is that estimates in literature are very sparse to absent, making it difficult to estimate cost developments towards 2050 for biomethane production with CO_2 capture.

Cost of biomass feedstock

Another important factor is the feedstock cost for MSW, sewage sludge and animal manure. This estimate can be considered optimistic or conservative, depending on the viewpoint. It can be considered optimistic from the viewpoint that collection and transport of these feedstock cannot be without cost and with it we are overestimating the economic potential. It can be considered conservative from the viewpoint that this waste type of feedstock often has negative economic value, i.e. money is paid to dispose this matter. If this would be the case, then we surely have underestimated the economic potential. We have chosen to assume the most neutral position: waste type feedstock do not have an economic value and collection and transport costs are allocated to the waste treatment; not to the biomethane production route.

Natural gas price and CO_2 price

The natural gas price is an important factor in our results. Increasing or decreasing the natural gas price has a strong impact on the economic potential of biomethane production routes. Part of our analysis is to integrate the CO_2 price into the price of biomethane. By implementing CCS into the biomethane supply chain, the CO_2 emissions are translated into a higher or lower price (when the cost of CCS is lower than the CO_2 price) for biomethane production. CO_2 emissions associated with converting natural gas are thus integrated into the price of the energy carrier. A CO_2 price of 20 €/tonne would result in a CO_2 premium of 1.1 €/GJ. A price of 100 €/tonne would result in a 5.6 €/GJ premium and has a substantial effect on the economic potential for biomethane production (see section 5.1 for the effect of increasing the natural gas price on the economic potential).

Connection and transport cost natural gas and CO_2 infrastructure
In our assessment of the economic potential, we assumed equal CO_2 transport costs for the gasification and digestion based routes. Furthermore, we excluded the costs of injecting biomethane in the natural gas infrastructure. This most likely results in an underestimation of the production cost of biomethane with CCS.

The scale difference between gasification and digestion (100s MW vs. 10 MW) will very likely lead to different infrastructural cost: small scale CO_2 transport as well as small scale gas transport, likely imposes higher costs for the digestion route. In order to keep digestion economically feasible, clustering of installations might be necessary. However, clustering possibilities are restricted by (wet) biomass availability. It is beyond the scope of this study to assess clustering possibilities for both routes in detail, but we recommend to study this in more detail.

Integration of biomethane production and end-use
Because a large share of the natural gas is currently consumed by large consumers (in power and industry), the options to integrate biomethane production with direct applications (for example power production), should be considered. A possible option would be to integrate a biogas production unit combined with a natural gas power plant with CCS. This would reduce the need for additional gas infrastructure and increases the amount of CO_2 that can be captured at one point. This however almost resembles an integrated gasification combined cycle studied earlier. The latter would most likely be a less expensive option to convert biomass into electricity and heat (cf (IEA GHG 2011)). The end-use of the biomethane is thus an important factor to take into account whether biomethane production with CCS is a sensible CO_2 mitigation option to consider.

7 Conclusions & recommendations

Main conclusions

- Biomethane production in combination with carbon capture and storage has the technical potential to remove up to3.5 Gt of greenhouse gas emissions from the atmosphere in 2050.
- Annual greenhouse gas emission **savings** could be almost 8 Gt in 2050 when natural gas is replaced by biomethane production with CCS.
- The economic potential depends strongly on the CO_2 price and natural gas price.
- Small scale biomethane production with CCS based on digestion is most likely restricted to niche market applications.
- Large scale gasification based production of biomethane with CCS could have potential in regions where large scale infrastructure is already in place for the transport of biomass, natural gas and CO_2.

The aim of this study is to provide an understanding and assessment of the global potential - up to 2050 - for BE-CCS technologies producing biomethane. We make a distinction between: *Technical potential* (the potential that is technically feasible and not restricted by economical limitations) and the *Economic potential* (the potential at competitive cost compared to the reference natural gas, including a CO_2 price). We studied two main technology routes for biomethane production: anaerobic digestion and gasification followed by methanation. Both production routes include the capture, transport and storage of the co-produced CO_2.

The main conclusion is that the technical potential for biomethane production with CCS ranges between 57 and 79 EJ in 2050. This is a significant potential considering the natural gas production of almost 110 EJ in 2008. Implementing the maximum technical potential would mean that up to 3.5 Gt of greenhouse gas emissions are removed from the atmosphere. Moreover, the substitution of 79 EJ of natural gas with biomethane would result in the avoidance of 4.4 Gt of CO_2 emissions. Greenhouse gas emission savings could thus add up to almost 8 Gt in 2050 on a global scale. It provides a significant reduction potential compared to the global energy-related CO_2 emissions which grew to 30.6 Gt in 2010 (IEA 2011).

The technical potential is the largest for the gasification based biomethane production. The potential for anaerobic digestion is smaller because of limited feedstock availability and lower average conversion efficiencies. Digestion is however a promising niche market technology for biomass with very high water content, such as sewage sludge and animal manure.

For both technology routes the availability of sustainable biomass limits the technical potential. The CO_2 storage potential and natural gas infrastructure are not likely to become a limiting factor for this potential.

Producing biomethane combined with CCS is economic attractive for about 14 EJ, resulting in about 1 Gt of negative GHG emissions. The economic potential for biomethane-CCS is dominated by the natural gas price in a region and the CO_2 price. For almost all combinations of feedstock (energy crops, agricultural residues and forestry residues) and conversion technology there is only an economic potential at natural gas prices higher than 14.2 €/GJ including a CO_2 price higher than 20 €/tonne. An exception is the use of municipal solid waste and sewage sludge in combination with anaerobic digestion which show already an economic potential at a CO_2 price of 20 €/tonne CO_2.

Drivers for the deployment of biomethane are (EU) targets for biofuels, security of supply (reducing the import dependency of natural gas),and the presence of existing natural gas transport and distribution infrastructure.

Barriers for the deployment of digestion-CCS are the high transport costs for the feedstock which limits the plant size. The small size of digesters most likely also results in high cost for connecting to the CO_2 and natural gas infrastructure. Niche applications are however possible. Anaerobic sludge digestion from municipal waste water treatment forms a good combination of biomass feedstock and conversion technology with important co-benefits. Further it is important for this technology route to look for possible valuable end-use of captured CO_2 to enhance business case for smaller systems with CO_2 capture (e.g. CO_2 use in industry, horticulture etc).

The gasification route fits best with a large scale infrastructure for the transport of biomass, natural gas and $CO_{2;}$ that is, a more centralised production of biomethane combined with CCS. The implementation of decentralised production of biomethane and end-use, in combination with CCS is deemed unlikely, due to infrastructural requirements for both CO_2 and natural gas.

Overall, we conclude that the economic potential for biomethane combined with CCS is most likely restricted to those regions that have favourable (high) natural gas and CO_2 prices, and have favourable infrastructural conditions. The latter encompasses the challenge to match the biomass supply infrastructure with that of natural gas and (developing) CO_2 infrastructure. We therefore recommend investigating locations, regions, industry clusters, which provide synergies for combining biomethane production with CO_2 removal and re-use or storage. A focus could be on regions with demand for CO_2 (industry, horticulture) or starting CCS infrastructure, (dense) natural gas infrastructure, high (local) availability of biomass and/or high natural gas import.

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Appendix A General assumptions

In this section the most important assumptions are presented. To assess the impact of our assumptions we have determined ranges of uncertainties for dominant assumptions. The impact of these assumptions is discussed throughout the main report. The main assumptions and their range of uncertainty are presented in the tables below.

Table A - 1 Overview of general assumptions used in this study (base case assumptions are highlighted)

Assumption	Unit	Low	Medium	High
Discount rate	%	6%	**10%**	15%
CO_2 price 2030	€/tonne CO_2	20	**50**	100
CO_2 price 2050	€/tonne CO_2	20	**50**	100
Gas price reference in 2030	€/GJ	9.47 – 14.20		
Gas price reference in 2050	€/GJ	9.47 – 14.20		
Animal manure and sewage sludge and MSW	€/GJ	**0**		
CO_2 transport costs	€/tonne CO_2	1	**5**	10
CO_2 storage costs	€/tonne CO_2	1	**5**	13
Annualised storage capacity factor	Years	30	**50**	70
Forestry residues potential	-	**Low**		High
Sustainability criteria biomass	-	**Strict criteria**	Mild criteria	No criteria
CO_2 Reservoirs type included	-	Hydrocarbon reservoirs only		**All**
Storage potential estimation	-	Low	**Best**	High

- All costs are given in Euro's (2010) unless otherwise stated.
- All efficiencies are based on lower heating value unless otherwise stated.

Table A - 2 SI prefixes

Prefix	Symbol	Quantity
Exa	E	1E+18
Peta	P	1E+15
Tera	T	1E+12
Giga	G	1E+09
Mega	M	1E+6
Kilo	k	1E+3

Table A - 3 Regional cost and price of biomass potential for energy crops, agricultural residues and forestry residues.

	Unit	Cost category biomass potential			
		1	**2**	**3**	**4**
Biomass production cost	€/$GJ_{primary}$	0.8	1.7	3.3	41.5
Ratio price/cost	-	4	3	2.5	1.2
Price	€/$GJ_{primary}$	3.3	5.0	8.3	49.8
Price (incl. densification and transport	€/$GJ_{primary}$	4.7	6.3	9.6	51.2
Price of biomass at factory gate	€/$GJ_{pellets}$	5.2	7.0	10.7	56.9
Biomass potential per cost category (cumulative)					
2030					
Region					
AFME	$EJ_{primary}$	1	5	6	13
ASIA	$EJ_{primary}$	1	5	8	17
OCEA	$EJ_{primary}$	0,3	2	2	5
LAAM	$EJ_{primary}$	0,4	3	11	15
NOEU	$EJ_{primary}$	0,3	2	2	5
NOAM	$EJ_{primary}$	1	4	7	13
OEU	$EJ_{primary}$	0,4	1	3	6
WORLD	$EJ_{primary}$	4	24	40	73
2050					
AFME	$EJ_{primary}$	2	8	10	23
ASIA	$EJ_{primary}$	2	9	14	30
OCEA	$EJ_{primary}$	0,5	3	4	8
LAAM	$EJ_{primary}$	0,8	5	19	27
NOEU	$EJ_{primary}$	0,5	3	4	7
NOAM	$EJ_{primary}$	1	7	12	21
OEU	$EJ_{primary}$	0,7	2	5	10
WORLD	$EJ_{primary}$	8	42	68	126

Appendix B Biomass potential

In this appendix, we give an overview of the biomass potentials specifically added in this study: Municipal Solid Waste (MSW), animal manure and sewage sludge. The potentials for energy crops, agricultural and forestry residues to refer to (IEA GHG 2011).

B 1 Biomass potential – sewage sludge and manure and municipal solid waste (MSW)

Manure & MSW

We used the potential estimates for MSW and animal manure potentials as assessed in (IIASA forthcoming). For MSW, (IIASA) assumed that the technical potential is equal to the economical potential (costs for transport and treatment can be allocated to waste-processing which is also necessary without extracting energy).

IIASA (IIASA forthcoming) assessed the economic potential of animal manure to be zero. We applied the technical potential, assuming there is an economically recoverable potential; digestion is already applied to animal manure, in developed as well as developing countries. It is however uncertain to what extent the technical potential can be harvested at low costs. This also depends on the scale of a typical digester, the density of cattle and the density of farms (allowing the option to cluster the feedstock of multiple farms).

Sewage sludge

The sewage sludge potential presented in Table B-1 is based on:

- The average amount of biomethane that can be extracted per unit of dry solid waste (B)
- The average amount of dry solid waste that is produced per capita per year (DSW)
- The number of people that are projected to be connected to a sewage infrastructure (P)

$$\text{Potential}_{\text{Sewage}} = B \times DSW \times P$$

We applied the average amount of biomethane per unit of dry solid waste and the amount of dry solid waste produced per capita as estimated by (Appels, Baeyens et al. 2008)

The number of people that are projected to be connected to a sewage infrastructure is based on

- Estimated number of people living in urban areas (per region) (U).

- Proportion of households in major cities that are connected to sewers (S).

$$P = U \times S$$

Both data are taken from statistics of the United Nations[19]. We assumed that the share of sewer connection in major cities reflect the share of sewer connections in urban areas. We also assumed developments in the share of sewer connections in the future.

Because our estimation is based on the amount of biomethane that can be extracted from the sewage sludge, the estimation reflects the *final* biomethane energy potential. The primary potential is based on the final potential, by applying the efficiency of digestion in reverse to the final potential.

Table B - 1 Regional breakdown technical sewage sludge potential in primary energy (EJ/yr) for view years 2030 and 2050

Regions	**2030**	**2050**
AFME	0.13	0.20
ASIA	1.07	1.39
OCEA	0.00	0.01
LAAM	0.19	0.21
NOEU	0.24	0.24
NOAM	0.31	0.35
OEU	0.24	0.24
WORLD	2.17	2.65

[19] **Urbanisation:** Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2008 Revision and World Urbanization Prospects: The 2009 Revision, http://esa.un.org/wup2009/unup/ Last accessed: 18 October 2011
Sewer connections: UN World Water Assessment programme – water and human settlements: http://webworld.unesco.org/water/wwap/facts_figures/water_cities.shtml Last accessed 10 January 2012

Appendix C Overview tables results

Table C - 1 Regional breakdown of the technical potential in primary energy (EJ/yr) for view years 2030 and 2050

Regions	Year	Technical potential			
		Gasification	Anaerobic digestion – EC and AR	Anaerobic digestion - MSW	Anaerobic digestion - Sewage/Manure
AFME	2030	13	9	0.7	1.0
ASIA	2030	17	11	1.4	2.6
OCEA	2030	5	3	0.5	0.2
LAAM	2030	15	10	0.8	1.0
NOEU	2030	5	2	0.3	0.9
NOAM	2030	13	7	0.8	1.0
OEU	2030	6	2	0.7	0.8
WORLD	2030	73.1	43.3	5.1	7.4
WORLD2	2030	73.0	43.3	5.1	7.4
AFME	2050	23	15	1.6	2.1
ASIA	2050	30	19	3.1	4.6
OCEA	2050	8	5	1.1	0.3
LAAM	2050	27	17	1.8	1.8
NOEU	2050	7	3	0.6	1.9
NOAM	2050	21	11	1.4	1.7
OEU	2050	10	4	1.0	1.4
WORLD	2050	125.6	74.7	10.6	13.8

Table C - 2 Regional breakdown of the technical potential in final energy (biomass share in EJ/yr) for view years 2030 and 2050

Regions	**Year**	**Technical potential**			
		Gasification	Anaerobic digestion – EC and AR	Anaerobic digestion - MSW	Anaerobic digestion - Sewage/Manure
AFME	2030	7.8	5.2	0.4	0.4
ASIA	2030	10.6	6.6	0.8	1.0
OCEA	2030	2.8	1.7	0.3	0.1
LAAM	2030	9.3	6.0	0.5	0.4
NOEU	2030	2.8	1.1	0.2	0.4
NOAM	2030	7.9	3.9	0.5	0.4
OEU	2030	3.6	1.5	0.4	0.3
WORLD	2030	44.8	26.0	3.1	3.0
WORLD2	2030	44.7	26.0	3.1	3.0
AFME	2050	14.2	9.2	1.0	0.8
ASIA	2050	19.0	11.5	1.9	1.8
OCEA	2050	4.8	2.8	0.7	0.1
LAAM	2050	16.7	10.5	1.1	0.7
NOEU	2050	4.7	1.9	0.4	0.7
NOAM	2050	13.4	6.5	0.9	0.7
OEU	2050	6.1	2.4	0.6	0.6
WORLD	2050	79.1	44.8	6.4	5.5

Table C - 3 Regional breakdown of the technical potential in negative GHG emissions (Gt CO_2 eq/yr) for view years 2030 and 2050

Regions	Year	Technical potential			
		Gasification	Anaerobic digestion – EC and AR	Anaerobic digestion - MSW	Anaerobic digestion - Sewage/Manure
AFME	2030	-0.3	-0.2	-0.02	-0.03
ASIA	2030	-0.4	-0.3	-0.04	-0.07
OCEA	2030	-0.1	-0.1	-0.01	-0.00
LAAM	2030	-0.4	-0.3	-0.02	-0.03
NOEU	2030	-0.1	-0.0	-0.01	-0.02
NOAM	2030	-0.3	-0.2	-0.02	-0.02
OEU	2030	-0.1	-0.1	-0.02	-0.02
WORLD	2030	-1.8	-1.1	-0.13	-0.19
AFME	2050	-0.6	-0.4	-0.04	-0.06
ASIA	2050	-0.8	-0.5	-0.09	-0.13
OCEA	2050	-0.2	-0.1	-0.03	-0.01
LAAM	2050	-0.7	-0.5	-0.05	-0.05
NOEU	2050	-0.2	-0.1	-0.02	-0.05
NOAM	2050	-0.6	-0.3	-0.04	-0.05
OEU	2050	-0.3	-0.1	-0.03	-0.04
WORLD	2050	-3.5	-2.1	-0.29	-0.38

Table C - 4 Regional breakdown of the technical potential in total CO_2 stored for view years 2030 and 2050

Regions	Year	Technical potential			
		Gasification	Anaerobic digestion – EC and AR	Anaerobic digestion - MSW	Anaerobic digestion - Sewage/Manure
AFME	2030	0.4	0.2	0.02	0.03
ASIA	2030	0.6	0.3	0.04	0.07
OCEA	2030	0.1	0.1	0.01	0.00
LAAM	2030	0.5	0.3	0.02	0.03
NOEU	2030	0.1	0.1	0.01	0.02
NOAM	2030	0.4	0.2	0.02	0.03
OEU	2030	0.2	0.1	0.02	0.02
WORLD	2030	2.4	1.2	0.14	0.20
WORLD2	2030	2.4	1.2	0.14	0.20
AFME	2050	0.8	0.4	0.05	0.06
ASIA	2050	1.0	0.5	0.09	0.13
OCEA	2050	0.3	0.1	0.03	0.01
LAAM	2050	0.9	0.5	0.05	0.05
NOEU	2050	0.3	0.1	0.02	0.05
NOAM	2050	0.7	0.3	0.04	0.05
OEU	2050	0.3	0.1	0.03	0.04
WORLD	2050	4.3	2.1	0.30	0.39