Sustainable Biomass Resources for Biogas Production

Mapping and Analysis of the Potential for Sustainable Biomass Utilization in Denmark and Europe

Meyer, Ane Katharina Paarup

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Meyer, A. K. P. (2015). *Sustainable Biomass Resources for Biogas Production: Mapping and Analysis of the Potential for Sustainable Biomass Utilization in Denmark and Europe*. Department of Energy Technology, Aalborg University.

SUSTAINABLE BIOMASS RESOURCES FOR BIOGAS PRODUCTION

MAPPING AND ANALYSIS OF THE POTENTIAL FOR SUSTAINABLE BIOMASS UTILISATION IN DENMARK AND EUROPE

by

Ane Katharina Paarup Meyer

AALBORG UNIVERSITY
DENMARK

Dissertation submitted August 2015

Thesis submitted:
August 2015

PhD supervisor:
Jens Bo Holm-Nielsen, Ph. D. Associate Professor
Head of Esbjerg Energy Section
Department of Energy Technology
Head of Centre for Bioenergy and Green Engineering
Niels Bohrs Vej 8, 6700 Esbjerg, Denmark.
Phone: +45 21 6625-11 e-mail: jhn@et.aau.dk

PhD committee:
Professor Lasse Rosendahl (chairman), Aalborg University, Denmark
Dr. Sc. Nat. Arthur Wellinger, Triple E&M, Switzerland
Senior Scientist Uffe Jørgensen, Aarhus University, Denmark

PhD Series: Faculty of Engineering and Science, Aalborg University
ISBN: 978-87-92846-62-4

ENGLISH SUMMARY

The aim of this thesis was to identify and map sustainable biomass resources, which can be utilised for biogas production with minimal negative impacts on the environment, nature and climate. Furthermore, the aim of this thesis was to assess the resource potential and feasibility of utilising such biomasses in the biogas sector. Sustainability in the use of biomass feedstock for energy production is of key importance for a stable future food and energy supply, and for the functionality of the Earths ecosystems.

A range of biomass resources were assessed in respect to sustainability, availability, and energetic feasibility by combining the use of a geographical information system with laboratory experiments, statistical analyses, field studies, and literature reviews. The biomasses identified as sustainable in this study were animal manure, straw, surplus grass from agricultural production, grass from nature conservation, and grass from roadside verges.

It was found that a significant potential of the investigated sustainable biomass resources are available in Denmark, but also on European level. In Europe, the energy potential in 2030 from animal manure, straw and surplus grass was projected to range from 39.3-66.9 Mtoe, depending on the availability of the residues.

Grass from roadside verges and meadow habitats in Denmark represent two currently unutilised sources. If utilised in the Danish biogas sector, the results showed that the resources represent a net energy potential of 60,000 -122,000 GJ and 640,000 GJ respectively. The energy return on energy investment when utilising roadside grass were estimated to range from 2.17 to 2.88, while 1.7 to 3.3 for the use of meadow grass. It was found that the concept of utilising grasses from nature habitats and roadside verges can function as a provider of renewable energy, a method for increasing the biodiversity of the nature habitats and roadside verges, and as a method for redistributing nutrients to the agricultural land

In the Region of Southern Denmark, an excess production of grass was estimated for several of the municipalities but the excess production was found to be quite sensitive to the management practice of the grass fields and the productivity of the grass. The estimated yields were found to be sufficient to serve as sole co-substrate in 2-16 biogas plants with a capacity of 200.000 t biomass annually.

Based on the results it was concluded that deteriorating and overuse of the ecosystems, as well as substitution of food and feed production does not have to be a precondition for bioenergy production. On the contrary, positive externalities from well managed bioenergy production systems can contribute in reducing

environmental problems, and prevent the loss of biodiversity without conflicting the food and feed supply.

DANSK RESUME

Formålet med denne afhandling var at identificere og kortlægge bæredygtige biomasser som kan udnyttes I biogas produktion med minimale negative påvirkninger på miljø, natur og klima. Endvidere havde afhandlingen til formål at vurdere ressource potentialet og mulighederne ved anvendelse af sådanne biomasser i biogas sektoren. Bæredygtighed i brugen af biomasse ressourcer til energi produktion er af central betydning for en stabil fremtidig forsyning med fødevarer og energi, og for funktionen af jordens økosystemer.

Ved at kombinere anvendelsen af et geografisk informations system med laboratorie eksperimenter, statistiske analyser, felt studier og litteratur studier, blev en række af biomasse ressourcer vurderet i forhold til bæredygtighed, tilgængelighed og energi balancen ved anvendelse. De biomasser som blev identificeret som bæredygtige i denne undersøgelse var husdyrgødning, halm, overskydende græs fra landbrugsproduktionen, græs fra naturbeskyttelsesområder og græs fra vejkanter.

Et signifikant potentiale af de undersøgte bæredygtige ressourcer blev fundet tilgængeligt i Danmark, såvel som på Europæisk niveau. I Europa blev energi potentialet i 2030 fra husdyrgødning, halm og overskydende græs projekteret til at repræsentere mellem 39,3-66,9 Mtoe, afhængigt af tilgængeligheden af ressourcerne.

Græs fra vejkanter og engområder i Danmark repræsenterer to uudnyttede ressourcer. Hvis de anvendes i den danske biogas sektor, repræsenterer ressourcerne et netto energipotentiale svarende til henholdsvis 60.000 -122.000 GJ og 640.000 GJ. Ratioen mellem energiudbytte i forhold til energiinvesteringer ved udnyttelse af vejsidegræs blev estimeret til at variere fra 2,17 til 2,88, mens ratioen for udnyttelse af græs var engområder blev estimeret til 1,7-3,3. Konceptet ved at udnytte græs fra naturområder og vejkanter kan fungere både som leverandør af vedvarende energi, en metode til at øge biodiversiteten i naturområderne og vejkanterne, såvel som en metode til at omfordele næringsstoffer til landbrugsjorden

For Region Syddanmark blev der beregnet en overskydende produktion af græs for flere af kommunerne, men den overskydende produktion viste sig at være følsom over for driften af græsmarkerne og vækstbetingelserne. Overskudsproduktionen blev estimeret til at være tilstrækkelig til at fungere som eneste co-substrat i 2-16 gylle baserede biogasanlæg med en kapacitet på 200.000 t biomasse årligt.

På basis af resultaterne blev det konkluderet at forværring og overforbrug af jordens økosystemer, samt substitution af fødevare- og foderproduktion behøver ikke at være en forudsætning for produktion af bioenergi. Tværtimod kan positive eksternaliteter fra velgennemtænkte bioenergi produktionssystemer bidrage til at

reducere miljøproblemer og forhindre tab af biodiversitet uden at påvirke forsyningen af fødevarer og foder.

ACKNOWLEDGEMENTS

Jens Bo Holm-Nielsen. The support and trust from you has meant everything during this journey. When the piles on my desk grew bigger than I thought I could manage, you always inspired and encouraged me to keep going on. It is impossible to stay unmotivated during your supervision. Thank you!

Lars Jürgensen. You have been a great colleague and friend all the way through. I hope the future will allows us to continue collaborating.

Ehiaze Augustine Ehimen. I cannot express how much I have appreciated your supervision and diplomatic approach towards me and my work.

Mette Skjærbæk. Your help, friendship and company, have been a life saver Thank you

Michael Kiuntke. Thank you for your endless love, support, and faith in me. Without you I never would have started or finished my PhD. I am looking forward to the next part of our journey together.

Sara Vyff. You have been a reliable supplier of coffee and company when I needed it the most. Thank you for always listening patiently to my frustrations and achievements.

My family. Thank you for always being there for me.

"In the middle of the 20th century, we saw our planet from space for the first time. Historians may eventually find that this vision had a greater impact on thought than did the Copernican revolution of the 16th century, which upset the human self-image by revealing that the Earth is not the centre of the universe.
From space, we see a small and fragile ball dominated not by human activity and edifice but by a pattern of clouds, oceans, greenery, and soils. Humanity's inability to fit its activities into that pattern is changing planetary systems, fundamentally. Many such changes are accompanied by life-threatening hazards. This new reality, from which there is no escape, must be recognized - and managed."

Our Common Future, Brundtland, UN, 1987

PREFACE

This dissertation is the result of my PhD work carried out in the frame of the EU financed Interreg4A project Large Scale Bioenergy Lab. Large Scale Bioenergy Lab was a transboundary project developing several facets of the bioenergy sector in the Region of Southern Denmark, and Northern Germany. Aalborg University Esbjerg, Denmark, was the lead partner in the project collaborating with Flensburg University of Applied Science, and Europa University Flensburg in Germany. The research conducted in the work forming this PhD dissertation focussed on the question of sustainability within the use of biomass resources for energy production. The PhD work was carried out from year 2012 to 2015 under supervision from Associate Professor Jens Bo Holm-Nielsen, Department of Energy Technology, Aalborg University Esbjerg. The majority of the research was carried out in Esbjerg, however one of the research papers were elaborated at Eberswalde University for Sustainability in collaboration with Dr. Caroline Schleier and Prof. Dr. Hans-Peter Piorr.

Besides this dissertation being a result of a transboundary project, it is also a result of an interdisciplinary belief. As a specialist in being a generalist, it has been exciting, but also challenging, to immerse myself into the field of biomass resources while not leaving behind the more holistic perspectives of sustainability. Many times during my PhD work I have wished for a more defined research field, but more than ever I also acknowledge the need for interdisciplinary research and actions.

The dissertation forms a collection of four research papers. An introduction to the aim, background, and approach for the research carried out are given in chapter 1-3. The key findings of the papers are presented in chapter 4-8, while the conclusions and perspectives are presented in chapter 9

MANDATORY PAGE

Thesis title:

Sustainable Biomass Resources for Biogas Production - Mapping and Analysis of the Potential for Sustainable Biomass Utilisation in Denmark and Europe

Name of PhD student:

Ane Katharina Paarup Meyer

Name and title of supervisor:

Jens Bo Holm-Nielsen, Associate Professor, Ph. D.

List of published papers:

Paper 1: Ane Katharina Paarup Meyer, Ehiaze Augustine Ehimen, Jens Bo Holm-Nielsen. "Bioenergy production from roadside grass: A case study of the feasibility of using roadside grass for biogas production in Denmark". Published in Resources, Conservation and Recycling 93 (2014) 124–133. http://dx.doi.org/10.1016/j.resconrec.2014.10.003

Paper 2: Ane Katharina Paarup Meyer, Caroline Schleier, Hans-Peter Piorr, Jens Bo Holm-Nielsen. The potential of surplus grass production as co-substrate for anaerobic digestion: A case study in the Region of Southern Denmark. Published in Renewable Agriculture and Food Systems, 20 July 2015.http://dx.doi.org/10.1017/S1742170515000277

Paper 3: Ane Katharina Paarup Meyer, Chitra S. Raju, Sergey Kucheryavskiy, Jens Bo Holm-Nielsen. The energy balance of utilising nature conservation grasses from meadow habitats in Danish biogas production. In print: Resources, Conservation and Recycling, Available online 1 October 2015. http://dx.doi.org/10.1016/j.resconrec.2015.07.019

Paper 4: Ane Katharina Paarup Meyer, Ehiaze Augustine Ehimen, Jens Bo Holm-Nielsen. The future of European biogas production – an outlook for 2030 focussing on sustainable biomass utilisation of animal manure, straw and grass. Submitted to Fuels, June 2015.

Proceedings:

A. Katharina P. Meyer; Jens Bo Holm-Nielsen; Department of Energy Technology, Aalborg University Esbjerg "Combining biogas production and nature conservation of protected nature habitats - the influence of transport distance, habitat size and accessibility to a road network in the region of southern Denmark" 21st European Biomass Conference "Setting the course for a biobased economy" June 3-7 2013.

Poster presentations

A. Katharina P. Meyer, Janni L. Skov, Jens Bo Holm-Nielsen, Department of Energy Technology, Aalborg University Esbjerg. "Nature Conservation of Lowland Grassland combined with Biogas Production and Sustainable Nutrient Recycling. Nordic Biogas Conference April 23-25 2012.

A. Katharina P. Meyer, Jens Bo Holm-Nielsen, Department of Energy Technology, Aalborg University Esbjerg. "Alternative substrates for biogas? – Sustainable use of grasses". Large Scale Bioenergy Lab conference September 3-5 2014.

Oral presentations on conferences, seminars and congresses:

The presenter is marked by a star.

A. Katharina P. Meyer*; Jens Bo Holm-Nielsen; Department of Energy Technology, Aalborg University Esbjerg "Biogas Production Based on Sustainable Biomass Resources". New Energy Husum (Germany), FURGY Congress, March 16, 2012.

A. Katharina P. Meyer*; Jens Bo Holm-Nielsen; Department of Energy Technology, Aalborg University Esbjerg "Combining biogas production and nature conservation of protected nature habitats - the influence of transport distance, habitat size and accessibility to a road network in the region of southern Denmark" 21st European Biomass Conference "Setting the course for a biobased economy" June 3-7 2013.

A. Katharina P. Meyer*; Jens Bo Holm-Nielsen; Department of Energy Technology, Aalborg University Esbjerg "Kortlægning af bæredygtige biomasse ressourcer i region Syddanmark & Schleswig K.E.R.N." Large Scale Bioenergy Lab seminar, Flensburg Fachhochschule, September 12, 2013 .

A. Katharina P. Meyer*; Jens Bo Holm-Nielsen; Department of Energy Technology, Aalborg University Esbjerg "Grass for bioenergy production in the Region of Southern Denmark – Schleswig K.E.R.N.", New Energy Husum (Germany), FURGY Congress March 21, 2014.

A. Katharina P. Meyer*; Jens Bo Holm-Nielsen; Department of Energy Technology, Aalborg University Esbjerg "Alternative feedstock's for biogas production in the Region of Southern Denmark – Schleswig K.E.R.N." Fachhochschule Flensburg May 16, 2014.

A. Katharina P. Meyer*; Jens Bo Holm-Nielsen; Department of Energy Technology, Aalborg University Esbjerg "Energibalancen ved udnyttelse af græs fra natur- og landskabspleje". Seminar om Biomasselogistik" SEGES, March 10, 2015.

A. Katharina P. Meyer*; Jens Bo Holm-Nielsen; Department of Energy Technology, Aalborg University Esbjerg "Biomass Potentials for Biogas Plants - Sustainable Grass for Bioenergy Production in The Region of Southern Denmark – Schleswig K.E.R.N." New Energy Husum (Germany), FURGY Congress, March 20, 2015.

A. Katharina P. Meyer*, Department of Energy Technology, Aalborg University Esbjerg; Caroline Schleier, Eberswalde University for Sustainable Development, Germany; Hans-Peter Piorr, Eberswalde University for Sustainable Development, Germany; Jens Bo Holm-Nielsen; Department of Energy Technology, Aalborg University Esbjerg. "An assessment of unutilised grass in Denmark perspectives of grass as feedstock for anaerobic digestion" Biogas Science 2014, Vienna. October 27-30, 2014.

This present report combined with the above listed scientific papers has been submitted for assessment in partial fulfilment of the PhD degree. The scientific papers are not included in this version due to copyright issues. Detailed publication information is provided above and the interested reader is referred to the original published papers. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty of Engineering and Science, Aalborg University.

TABLE OF CONTENTS

TABLE OF FIGURES

ACRONYMS

Mtoe	Million Tonnes of Oil Equivalents
GJ	Giga Joule
K.E.R.N.	Kiel-Eckernförde-Rendsburg-Neumünster
NEG	Net Energy Gain
EROEI	Energy Return on Invested Energy
GIS	Geographical Information System
EEG	Erneuerbare-Energien-Gesetz (the German Act on Renewable Energy Sources)
Ha	Hectares
GPS	Global Positioning System
EU	European Union
TS	Total Solids
VS	Volatile total Solids
FU	Feed Unit

1 INTRODUCTION TO THE PHD STUDY

The research conducted in this Ph.D. thesis was drawn from a work package in the EU financed Interreg4A project “Large Scale Bioenergy Lab”. The purpose of the project was to develop and test technical, economic, and environmentally sustainable solutions relating to the use of biomass in biogas plants and biorefineries in the regions of Southern Denmark and Northern Germany (figure 1). The concerned work package in the project focussed on the question of sustainability within the use of biomass resources in the project regions.

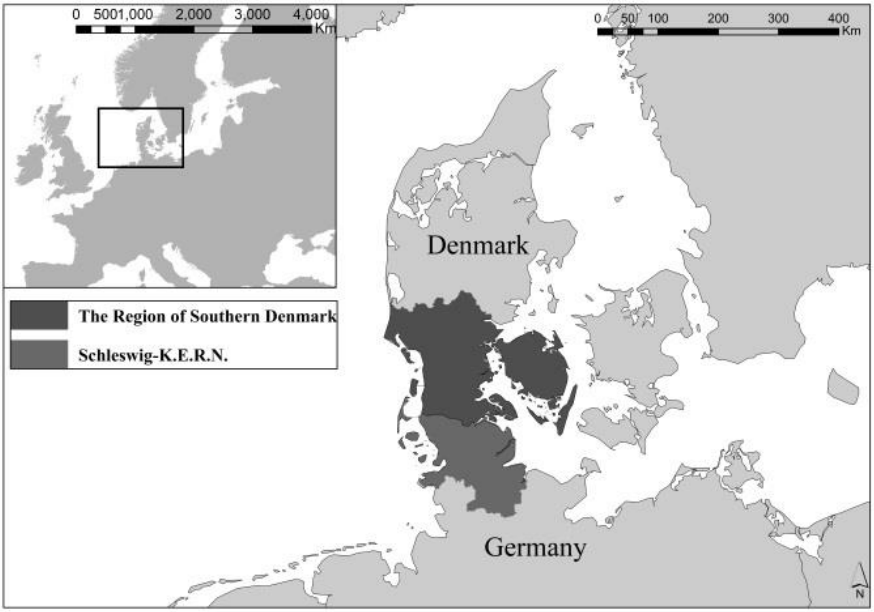


Figure 1: The Region of Southern Denmark and Schleswig- K.E.R.N.(Kiel-Eckernförde-Rendsburg-Neumünster).

1.1. THE CHALLENGES IN THE REGIONAL BIOGAS SECTOR

The motivation for the work conducted in this thesis has had it primary base in the challenges related to the development of the renewable energy sector in the regions of Southern Denmark and Northern Germany. Despite the regions being similar in many ways the bioenergy sectors have developed differently. Majority of the regions geographic extents are classified to be in the same environmental zone which is dominated by the influence of North Sea. Thus the climate of the regions is rather humid and with relatively mild temperatures during summer and winter (Metzger et al., 2005). Both regions are dominated by having a large share of agricultural land, but a moderate population density (table I)

Table I: Demographics and agricultural land use in the Region of Southern Denmark and Schleswig-K.E.R.N.(Statbank Denmark, 2015a; Regionaldatenbank Deutschland, 2013; Eurostat, 2015a)

2013	The Region of Southern Denmark	Schleswig-K.E.R.N.
Population	1,201,419	1,039,733
Total area in km^2	12,256	6,588
Inhabitants per km^2	98	156
Share of agricultural area	63%	73%

In the German region, more than 300 biogas plants are in operation of which many are farm scale plants. In the Danish region, approximately 20 medium to large scale biogas plants are established. The high number of biogas plants in the German region is caused by a favourable feed-in tariff for electricity produced from biogas promoted by the German Act on Renewable Energy Source (EEG).

In Denmark, the Danish Parliament is aiming at expanding the Danish biogas sector by targeting the use of 50% of the available manure in the country by 2020. This is to be achieved by the means of an improved scheme for financial support for biogas producers. The feedstock use for biogas production has also developed differently in the regions. In Denmark, feedstock sources typically have been animal manure and industrial organic residues, whereas in Germany, the use of energy crops (especially maize) has increased significantly. It is assessed that energy crops (maize and beets) cultivated on ≈ 1,000 ha in Denmark are consumed for biogas production in the country while ≈ 11,000 ha of maize crop are cultivated in the Southern Denmark region, and exported specifically to biogas producers in Northern Germany (Madsen & Larsen, 2011). The increasing cultivation of maize for biogas production, which both regions have been facing during the recent years, initiated a public aversion towards maize. In Denmark, the adoption of the improved financial scheme for biogas producers has also led to concerns that this could encourage increased use of energy crops as co-substrates for biogas production. This concern resulted in restrictions in the financial scheme, limiting the quantity of purposely grown energy crops that can be used in biogas plants (The Danish Energy Agency, 2012). In Germany, restrictions on the use of energy crops were also implemented by amendments in the EEG. One of the main changes was the withdrawing of the possibilities of receiving financial benefits for biogas production based on energy crops (EurObserv'ER 2014).

Considering these changes in the legislative framework conditions for biogas producers in the regions, it seems that a shift in the feedstock use is expected for the future development of the biogas sector. This, however, generates significant challenges for the biogas producers in both regions. In the German region, economically viable alternatives to the energy crops currently being used must be found in order to keep the existing plants in operation. In the Danish region, the targeted establishment of more manure based biogas plants requires a supply of co-substrates for boosting the biogas production, due to the high moisture content in animal manure.

1.2. THE AIM

The aim of this thesis was to identify and map sustainable biomass resources in the project regions, which can be utilised for local biogas production with minimal negative impacts on the environment, nature and climate. Furthermore, the aim of this thesis was to assess the resource potential and energetic feasibility of utilising such biomasses in the regional biogas sector.

2 BACKGROUND

The geographical range of the research conducted in this thesis extends to the regions of Southern Denmark and Northern Germany. The national legislative framework conditions for biogas producers in both countries have recently moved towards a more sustainable utilisation of biomass resources for biogas production. The reason for this movement is primarily based on national or European motives; however, sustainable use of biomass resources is of global significance.

Although the background for this research origin from challenges within a local context, proposed solutions must consider and embrace the more holistic context in order to ensure sustainability. The purpose of this chapter is to outline this contextual background.

2.1. THE GLOBAL CHALLENGES

By using the planetary boundaries approach, Steffen et al. (2015) assesses that four, out of nine, boundaries which define a safe operating space for humanity has been crossed: climate changes, biosphere integrity, land-system change and biogeochemical flows (figure 2). The trespassing of the four boundaries is related to the way we utilise global resources. Climate changes are mainly caused by the use of fossil fuels for energy production, but also the destruction of nature habitats contributes to climate changes as their function of carbon stocks are destroyed. Agricultural production and urbanisation can be argued to strongly impact the other three planetary boundaries, as land use and land use changes has transformed majority of the natural ecosystems of the world into being dominated and impacted by anthropogenic activities. Food production is however a necessity for survival, and due to the increasing world population more food will be needed in the future.

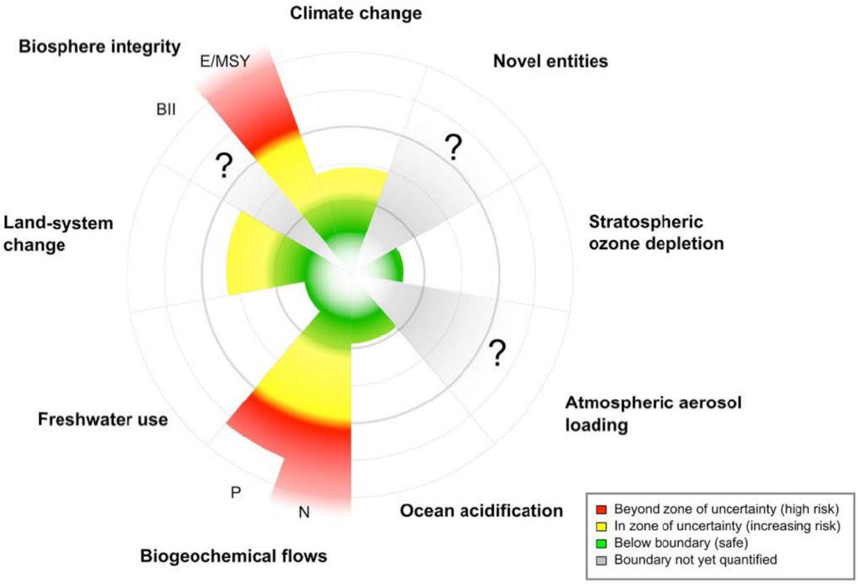


Figure 2 Four out of nine planetary boundaries defining a safe operating space for humanity has been trespassed (Steffen et al., 2015).

Whereas the consequences of climate changes already receives widespread attention, increased focus on the consequences of changing the biosphere integrity, land use and biogeochemical flows is also needed. The human impacts on the functioning and resilience of the Earth System and their interdependent relationships are complex to estimate and fully understand. Solutions embracing all these issues are nevertheless required to maintain the functioning and resilience of the Earth System, ensuring that the next generations of the world population has the same opportunities as we have today.

2.1.1. THE NEEDS OF THE HUMAN POPULATION

Anthropogenic activities are considered to be the main factor influencing the state and functioning of the Earth systems. Despite significant differences in the living standard of the world’s inhabitants, food and energy are basic resources needed by all inhabitants. In order to make the consumption of energy and food sustainable, these resources should be utilised in a manner that ensures that the next generations of the world population has the same opportunities as the past generations. Nevertheless, the tendency has been, and still is, that several communities of the world strive for survival and prosperity with little regard to the future generations.

The population of the world has passed 7 billion and is steadily increasing. In the industrialised communities it seems to be given that the population can maintain, or improve their way of living in respect to their diets, transportation methods, technological devices etc. In communities which have not yet undergone the industrialisation, parts of the population are struggling to acquire the basic products necessary for survival. A sustainable development can be defined to be a development that ensures that the next generations of the world population has the same opportunities as the past generations; nevertheless, the generations of the world today do not have equal opportunities in respect to living standards. However, at the current state, where the resources extracted are not even sufficient to cover the basic needs of all inhabitants, our utilisation of the globe cannot be considered to be sustainable.

2.1.2. OUR RELIANCE ON THE ECOSYSTEMS

The Millennium Ecosystem Assessment (2005) defines an ecosystem to be a dynamic system of plant, animal, and microorganism communities and the non-living environment interacting as a functional unit. Typical examples of ecosystems are forests, lakes, and grasslands. Ecosystems can be of any size, but usually they have no fixed boundaries. The entire planet can thus be considered to be an ecosystem. The ecosystems of the world are suppliers of a range of services referred to as ecosystem services. These services include benefits that are obtained by the human population. Providing services, such as food, fuel, timber, and water, are probably the most obvious categories of ecosystem services, but also regulating services (i.e. water purification, and flood and disease control), cultural services (i.e. recreational and aesthetic benefits), and supporting services (i.e. photosynthesis, nutrient cycling, and soil formation) are vital services provided by the ecosystems (Daily, 1997). By using the provisions of the ecosystems, humanity is able to supply itself with needed and desired goods. However, a continuous and uncritical use can have fatal consequences for the ecosystems (Tilman, 1999; Foley et al., 2005). In fact, the Millennium Ecosystem Assessment (2005) estimates that globally 60% of the ecosystem services are already deteriorating or overused due to anthropogenic activities.

The functioning of the ecosystems have been argued to be strongly related to biodiversity (Maestre et al., 2012), but a complete understanding of how biodiversity determines the ecosystem functioning is not yet fully addressed. Biodiversity can be defined to be the variability among living organism and the ecological complexes of which they are part (Millennium Ecosystem Assessment, 2005). The loss of a given species in an ecosystem thus alters the community of an ecosystem, and its interaction with the environment or other ecosystems. This may change the provision of the ecosystem services associated with the extinct species (Bennett et al., 2009).

To avoid further losses of biodiversity and ecosystem functions, international initiatives has been introduced (i.e. the Convention on Biological Diversity, and the Millennium Ecosystem Assessment). Whereas initiatives implementing strategies for conservation and restoration of natural habitats and species often are associated with non-use values such as aesthetic and recreational improvements, the implementation should also be encouraged for utilitarian reasons. Basically, the human population relies on the supply of fresh water, food, fuels, and timber, thus ecosystem services are a necessity for our survival. But also our economies use large amounts of provisional ecosystem services as inputs for production and consumption, thus the resources can be considered as a stock of natural capital. By sustaining the ecosystems, the services they provide can continue to supply the current human population and the following generations with the resources they need. However, due to the current deterioration and overuse of the ecosystems one can question if the ecosystems are able to continuously support us with the supplies we need to maintain our living standards.

2.1.3. CHANGING THE CLIMATE

Since the industrial revolution, society in the developed countries of the world have transformed profoundly. The technological development accelerated rapidly, living standards increased and population grew. Consequently, an externality referred to as “the biggest market failure the world has seen” (N. Stern, 2008) made its entry. The emission of anthropogenic greenhouse gases has been continuously increasing and the atmospheric concentration is at a level unprecedented in at least the last 800,000 years (Pachauri et al., 2014). Despite the hypothesis of the environmental Kuznets curve, proposing that there is an inverted U-shape between environmental degradation and income per capita (D. I. Stern et al., 1996; Shafik, 1994), the greenhouse gas emissions have not been found to decrease yet. Irrespective of observed parallel changes in the atmospheric concentration of greenhouse gases and climate since the beginning of the 20th century (Pachauri et al., 2014), a debate on whether climate changes are anthropogenic, natural, or both, is still ongoing. Regardless of ones convictions on the greenhouse effect and the causes for the climate changes, it should not be questionable that the precautionary principle (“guilty until proven innocent”) is the better one to follow, in a case where consequences can cause severe damage on the globe and for our existence.

Climate changes caused by increasing atmospheric concentration of greenhouse gases are considered to be one of the biggest threats towards our globe and the human population. As the climate fundamentally controls the distribution and functioning of the ecosystems (Staudinger et al., 2012), increasing greenhouse gas emissions may not only impact the weather conditions of the globe but also the vital ecosystem services necessary for the existence of the human population and the future generations. Thus, the direct overuse and deterioration of the ecosystem services caused by human consumption are reinforced by the climatological changes caused by the increasing emission of greenhouse gases.

2.2. ENHANCING THE CHALLENGES

The challenges described in the previous chapter can be summarised to be caused by one main source: anthropogenic activities. The efforts for maintaining or improving the living standards of the human population has required consumption of large amounts of natural capital and will continue to do so. A continuous overuse and deterioration of the ecosystems can have fatal consequences for the vital services they provide, thus the resources needed for human survival may vanish. As assessed by Steffen et al. (2015) anthropogenic activities has caused that four, out of nine, boundaries which defines a safe operating space for humanity is already crossed. Whereas some negative effects directly or indirectly caused by anthropogenic activities have been rectified through the implementation of remedial actions (i.e. the depletion of the ozone layer) other changes are irreversible (i.e. the extinction of species, and the build-up of greenhouse gases in the atmosphere). By discontinuing these anthropogenic activities, an increase of the negative effects can however be prevented.

2.2.1. SUPPLYING THE WORLD WITH FOOD AND ENERGY

The challenge of feeding a growing world population while ensuring that the ecosystems are not being further destroyed seems invincible. Foley et al. (2011) however, argues that changing the current agricultural strategies could double food production while reducing the environmental impacts of agriculture. According to their analyses this can be done by increasing the crop yields on underperforming agricultural land areas, stopping the expansion of agriculture into sensitive ecosystems, increasing agricultural resource efficiency, shifting diets, and reducing food waste. The solution for avoiding further deterioration of the ecosystem services while supplying the world population is thus complicated and requires several actions.

The solution for avoiding increasing climate changes can seem simpler, as the source for the problem emerges from one single action: the emission of greenhouse gases. In other words, the key is to prevent that the atmospheric concentration of greenhouse gases increases further by cutting our emissions. The main method for doing this is to phase out the consumption of fossil fuels and replace them with renewable resources.

Means for increasing the production of renewable energy are being implemented worldwide. In 2013 the global consumption of renewable energy was estimated to represent 19.1% of the total energy consumption and this figure is projected to increase to 30-45% in 2050 if the renewable energy sector develops moderately (REN21, 2013; REN21, 2015). Almost half of this consumption is derived from the traditional conversion of biomass (primarily used for heating and cooking in developing countries), while the remaining derived from more modern energy conversion methods (hydro power, geothermal power, wind power, solar power and biofuels). In the European Union the share of renewable energy sources in the energy supply reached 15% corresponding to ≈197Mtoe in 2013. Sixty-five percent of the total production of renewable energy originated from biomass and renewable waste (European Commission, 2015; Eurostat, 2015b; Eurostat, 2015c). Energy deriving from biomasses thus represents a large share of the renewable energy production on global level, but also in European level.

2.2.2. WHY DEAL WITH BIOMASS?

Sources for energy like wind and solar power are inexhaustible. They cannot be depleted by human activities, nor does the utilisation of them impact the ecosystem services that provide food for the human population. Thus, the utilisation of such energy sources is the obvious pathway for a transition towards a global energy supply which is not based on fossil fuels.

Considering that the challenge of supplying the growing world population with sufficient yields of food requires dramatic changes in the global agricultural strategy, it can be questioned if the future energy supply should rely on sources, such as biomass, that requires further utilisation of the natural resources provided by the ecosystems. Bioenergy however, still represents a significant share of the global energy consumption and is subject to increasing research and development. Compared to other renewable energy sources, biomass has a range of advantages which cannot be neglected in the attempt of phasing out the use of fossil fuels.

Biomass is a versatile source for energy that can be converted into several end products such as power, heat, and solid, liquid, and gas fuels. Biofuels in particular are relevant for replacing the use of fossil fuels in the heavy transport sector, where other renewable energy sources are not suitable. Biomass and its end products can be stored with only minor energy losses and used on-demand. Thus it is a stable and reliable energy source, compared to the fluctuating production of energy from wind and solar. The use of biomasses also has other vital advantages in the context of phasing out the use of fossil raw materials. Fossil raw materials are not only a source of energy, but also a source of carbohydrates. Petroleum can be refined and is used in the production of several products such as plastics, chemicals, and pharmaceuticals. In this context, Kamm & Kamm (2007) discussed that biomass can be refined into a range of end products similar to petroleum-based products (figure 3). Thus biomass can potentially replace the use of petroleum in the production of these products.

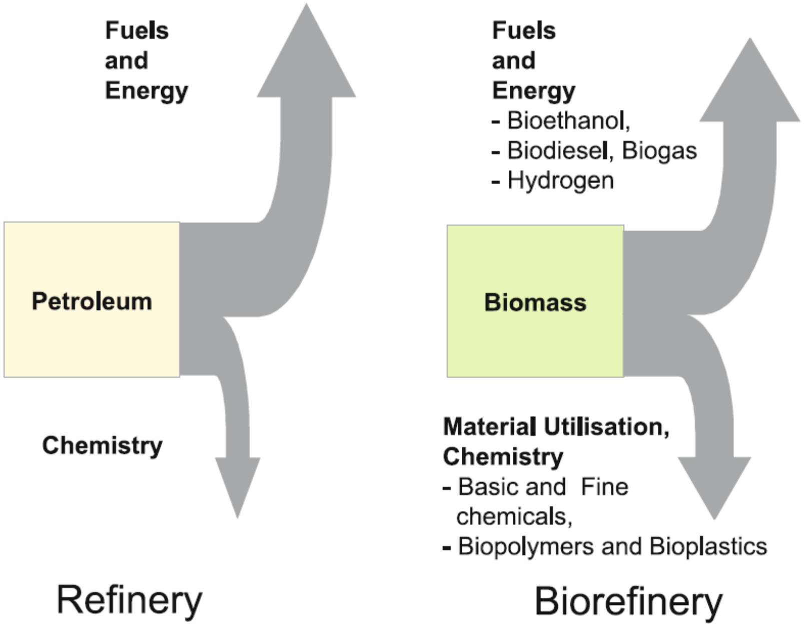


Figure 3: The basic principles of petroleum refinery and biorefinery (Kamm & Kamm, 2007).

The use of biomass could therefore prove essential for a stable and reliable future renewable energy supply, and as an alternative to the production of petroleum deriving products.

2.3. BIOENERGY

The use of biogenic resources for energy production has taken place since people began using firewood for heating and cooking purposes. In many developing countries biomass is still the primary energy source, but an increasing use of biomass for energetic purposes is also taking place in the developed countries, due to the demand for renewable energy.

Wood is largest contributor to the world´s bioenergy production, but also energy crops, residues from agriculture and forestry, and municipal and industrial waste are also used for energy production. Applicable for all of them, are that in order to be renewable the quantity of biomass used for energy production must be equal to (or less) than the quantity of biomass that is regrown. Renewability is an essential factor in the worlds energy supply due to the increasing emissions of anthropogenic greenhouse gases in the atmosphere, as well as the future limitation in the fossil fuel supply. Renewability should however not be the only measure for assessing whether or not the use of a biomass for energy production is sustainable. If not thoughtfully considered, utilisation of biomass resources can result in the destruction of valuable nature habitats with high biodiversity, nutrient leaching, pollution with chemicals, so as it may compete with food production on agricultural land, causing direct and indirect land use changes.

The potential reduction of greenhouse gas emissions is one of the main drivers for utilising biomass resources for energy production. In Europe, the European Commission has set a goal of 20% of all energy consumed by the year 2020 consisting of renewables. In this context biomass derived energy production has received increasing interest. In particular, the European biogas production has increased six fold from year 2000 to 2013 (Eurostat, 2015d), reaching 13.5 Mtoe in 2013. Three main categories of biogas production exist: landfill gas (24%), sewage sludge gas from digestion municipal and industrial waste (10%), and digestion of other organic materials (67%) (EurObserv'ER, 2014). The last category covers the utilisation of a large range of biomasses, such as organic household waste, agricultural residues, and energy crops. In the future development of the European renewable energy supply, biogas production can represent a key pillar. It is a well demonstrated technology present in majority of the European Union member states, and it ensures a flexible energy supply as it can be stored and used when needed.

2.3.1. PATHWAYS OF BIOENERGY PRODUCTION

Several pathways for converting biomass into useful forms of energy exist. In general, it is necessary to use a conversion technology in order to make the energy in biomass available for use. Figure 4 illustrates the main routes for energy conversion of biomasses (Turkenburg et al., 2000). Combustion is a direct method which generates heat, but the biomass can also be transformed into solid, liquid, or gaseous energy carriers, from which heat and electricity can be produced. Thermochemical conversion methods implies the use of heat or/and chemical agents, whereas biochemical requires the use of enzymes from bacteria or other microorganisms (Dahiya, 2014).

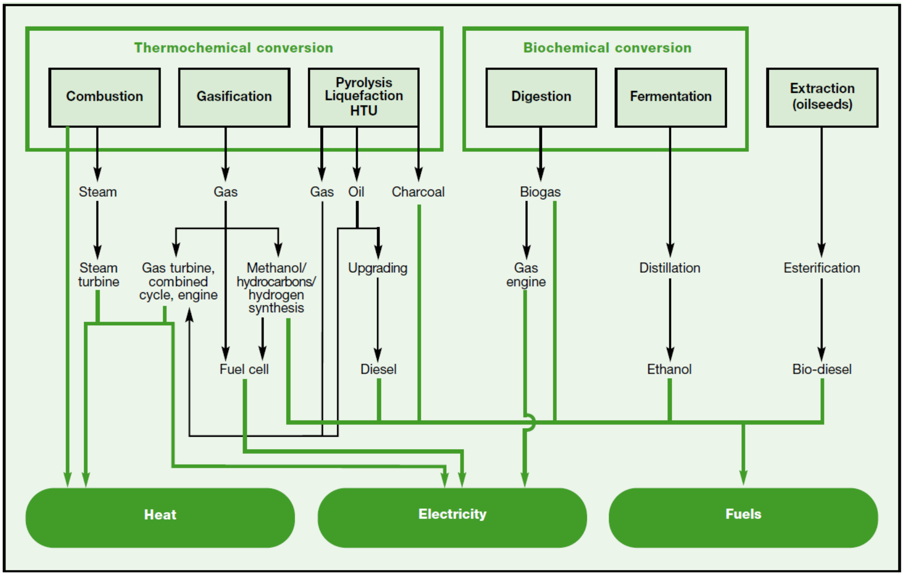


Figure 4 Main routes for energy conversion of biomasses (Turkenburg et al., 2000)

The applicability and efficiency of the conversion technologies depends on the characteristics of the biomass being processed i.e. moisture content, caloric value, cellulose/lignin content But also the end-use requirements, environmental standards, and economic conditions, influence the choice of conservation method (McKendry, 2002a; McKendry, 2002b). Although several conversion technologies exist, and are under continuous development, not all of them can be considered as cost effective or applicable for large scale application.

Anaerobic digestion plants have been known since the 19th century and were originally established for waste water treatment purposes. Gradually, anaerobic digestion plants also found its way into the agricultural sector (Jørgensen, 2009) where they serve multiple purposes. Anaerobic digestion plants represents a unique platform for recycling nutrients, thus closing the cycles of important resources, which if not controlled correctly could cause environmental negative impacts (Holm-Nielsen et al., 2009). Today, anaerobic digestion of biomass is a well-established technology which takes place on both small and large scale levels.

2.3.2. FEEDSTOCK'S FOR BIOENERGY PRODUCTION

Generally biomass can be classified in two groups: woody and non-woody biomass. Woody biomass consists of mainly lignocellulose, which has little or no food value. Non-woody biomass consist of sugars/starches, cellulose/lignocellulose, and lipids. Sugars and starches can be found in the edible parts of food crops, such as maize grains. Cellulose and lignocellulose are typically found in in leaves and stems of plants, while lipids derive from i.e. algae and seeds (Dahiya, 2014).

Both woody and non-woody biomass feedstock used for bioenergy production usually origins from the agricultural and forestry sectors, but they can also be industrial or municipal waste products. In general all plant based materials can be used for energy production, but the specific characteristics of the biomass will determine which type of conversion technology that is most efficient to apply. Woody biomass types with low moisture contents are often used for thermochemical conversion, while non-woody biomass types with higher moisture contents are more applicable for biochemical conversion methods. Biochemical conversion of non-woody biomasses consisting of lignocellulose however requires pre-treatment in order to break down the cellulose and hemicellulose into sugars and other fermentable materials.

The applicability of plant biomass cultivated intentionally for energy production (energy crops) is under increasing research and test. The cultivation of high yielding crops with low production costs are very promising substrates, but also the utilisation of biological residues poses interesting possibilities for bioenergy production. Bioenergy can thus be produced from very diverse substrates. Regardless of the origin of the feedstock, the choice of feedstock should be considered carefully in respect to the potential impacts the utilisation can cause on the ecosystems and the global food supply.

2.3.3. A RENEWABLE ENERGY SOURCE

Renewability is a key parameter for the future energy supply. The terms “bioenergy” and “renewable energy” have often been presented in the literature as being synonymous, assuming that all materials derived from earth are inexhaustible. The basic prerequisites for biomass growth are sun light, water, carbon-dioxide (CO_2), nutrients and soil minerals. Sunlight can be considered an inexhaustible resource, whereas water, CO_2, nutrients and soil minerals are parts of the cycles of the Earth systems and bound within these. The prerequisites for biomass growth will always be present in the ecosystems, thus in theory biomass is a renewable resource.

In order to renew a supply of biomass, the regrowth of new plant materials is necessary. Thus, the first condition for bioenergy to actually be renewable is that investments are put in creating the conditions necessary for plant growth. Due to the problems of increasing concentrations of CO_2 in the atmosphere, the balance between CO_2 uptake and emissions are often used as a measure of renewability within bioenergy production. The regrowth of biomass should capture at least equal, or larger, quantities of the CO_2 released for the energetic utilisation of the biomass used. This approach however does not consider if the re-cultivated/re-growing biomass is the same as the original biomass being used.

On cultivated agricultural areas it may not be a current issue, considering that the original natural landscape is long gone. But if biomass from currently natural areas are being exploited or converted into energy crop plantations, it can create negative impacts on the biodiversity and ecosystems of the areas (Matson et al., 1997). Thus, although biomass can be renewable in quantitative measures, it is not necessarily renewable from a qualitative perspective.

2.3.4. GLOBAL PROBLEMS – LOCAL SOLUTIONS

Despite the problems the world is facing (presented in Chapter 2.1) being of global character and significance, they must be solved locally or regionally. The diversity of the world’s societies in respect to i.e. agricultural production, population, economy, diets, technological development, climate, policies, flora, and fauna makes the specific solutions needed for a future sustainable food and energy supply just as diverse and challenging. No “all inclusive” solution exists, except from stopping all anthropogenic activities, but a wide range of different methods utilising the strengths and possibilities in the in local societies must be applied.

In the context of bioenergy production this means that a range of different feedstock, which can be extracted/acquired with no or little negative impact on the ecosystems, food supply and climate, should be applied. The utilisation of these feedstocks must furthermore be designed in a way that fits to the needs of the local society and their energy systems. Whereas some societies already have a well-developed renewable energy system and infrastructure, others are lacking both. Therefore, it can be a great challenge to shift to a more sustainable, but also affordable renewable energy supply.

Another aspect is that the distribution of renewable energy sources does not always match the distribution of the energy demand. A robust and capable energy infrastructure connecting the production sites and the consumers are thus a necessity for efficient utilisation of the energy. In other words, solutions for the specific resource acquisition and utilisation must be found locally, whereas the energy distribution systems must be transboundary and connected to international electricity and gas grids. .

3 RESEARCH APPROACH

This chapter serves as a general introduction to the methodical framework used in this study, whereas the detailed description of the applied methods and materials can be read in the individual research papers. A geographical information system (GIS) was used consistently as a tool in all the research areas of this thesis. A brief introduction to the concepts of GIS is therefore given in section 3.1.

The overall methodology of this thesis can be divided into three steps:

I. Assessment of the sustainability

II. Assessment of the availability

III. Assessment of the energetic feasibility

Identification of sustainable biomasses for further research was the initial step of the conducted work. The approach for the biomass identification is presented in section 3.2. Secondly, the availability of the identified biomass resources were assessed as presented in section 3.3. In the last step was the feasibility of utilizing the identified biomass resources assessed as presented in section 3.4.

3.1. GEOGRAPHICAL INFORMATION SYSTEMS

GIS is the acronym for a Geographic Information System, but the acronym is also used for geographical information science or geospatial information studies. For this thesis it will refer mainly to Geographical Information Systems.

A GIS is a software tool with very versatile application possibilities for analysis and it can be used on all spatial levels. With GIS digital maps, data with geographical registrations can be managed and visualized, thus information about the real world can be processed and presented on a computer. Most researchers associate GIS with visualization of data and the generation of maps. Data plotted on a map can reveal specific pattern and relationships not clearly visible in tabular datasets. GIS can however also be used for more complex analysis based on the spatial relationship between different types of data (Swanson, 2001).

3.1.1. FROM REALITY TO COMPUTER

In order to process information about the real world on the computer, information representing the real world must be digitalized. In other words, a transformation of the physical world to a digital world must take place. The digitalization of analogue country maps has played an important role in this context.

Figure 5 shows a section from an analogue map of Denmark published in the period of 1957-1976 (The Danish Geodata Agency, 1976). As it shows, several topological attributes of the area were already mapped back then, by the use of different colours, shapes, lines and points. Roads, contour lines, water bodies, nature areas, and cadastres can be read from the map. By digitalizing such maps all the information can be retrieved to a GIS and analysed on a computer. Today the application of i.e. GPS based field computers and remote sensors contributes significantly to the registration of real world phenomena in the digital representation.

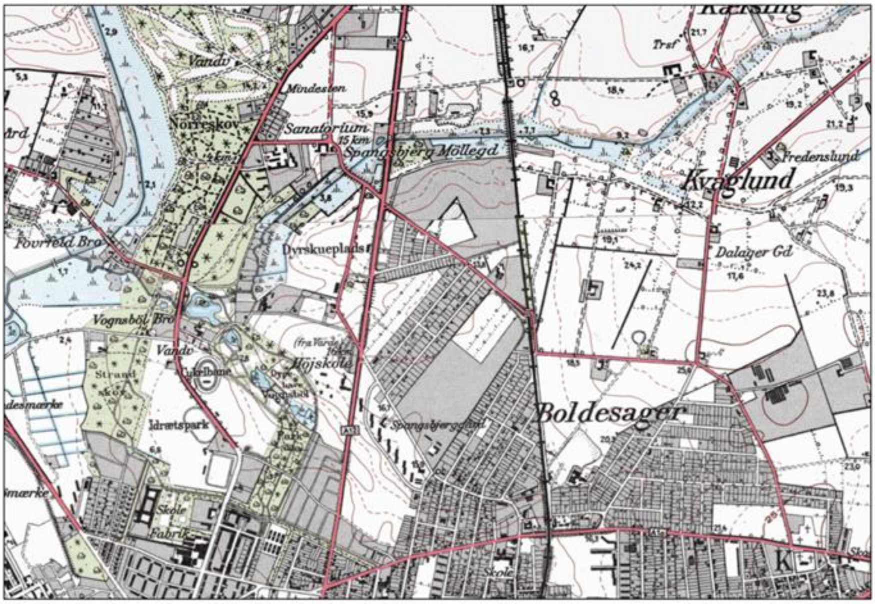


Figure 5 A section from an analogue map of Denmark published in the period of 1957-1976(The Danish Geodata Agency, 1976)

The modelling of the physical world into a digital representation requires that both the individual units and the holistic context are simplified, as both contain an infinite amount of information. The two foremost methods for data modelling in GIS are: vector based modelling and raster based modelling. In vector based models the features of the reality is presented by points, lines and polygons. Points are presented by their x, y coordinates and a line by two or more x, y coordinate pairs in the particular projection system. Polygons are presented by at least three lines that create a closed figure. In raster based models the features of the reality is presented by using a grid consisting of equal sized squares (grid cells), where each grid cell represents a portion of the reality (Wise, 2014; Balstrøm et al., 2006).

3.1.2. ATTRIBUTES

In vector and raster modelling, each geographical registered feature can be assigned with different attributes. Attributes consists of non-spatial information about the feature, and can both be a value or a text (Balstrøm et al., 2006). Figure 6 shows the coordinates of a point object in Denmark. The coordinates represents the location of a biogas plant, thus the point is assigned with the attribute that it is a biogas plant. Further details about the biogas plants which can be read from the assigned attributes are i.e. that it is a farm scale biogas plant and that is located in the municipality of Vejen.

Coordinates	Type	Name	Address	Zip code	City	Municipality	Region
8°54'23.297"E 55°32'26.136"N	Farmscale	Skovbækgård Biogas	Treagervej 10	6670	Holsted	Vejen	Syddanmark

Figure 6 An attribute table from a point object in a geographical information system

Attributes can contain any information, such as descriptions, measurements, and classifications of geographic features.

3.1.3. LAYERS

Digital maps or geo-datasets are often organised in layers. Each layer can represent information about a certain theme. A digital road map can be categorized in different layers according to i.e. the road classification. A map can also be categorized in layers according to the types of features in the map, such as contour lines, roads and administrative units. When projected to the same coordinate system, layers from different digital maps can be applied together in order to assess the spatial relationship between different themes. This is exemplified in figure 7 which illustrates how different layers from different geo-datasets in this study were applied together in order to investigate the spatial relationship of fields, soil types, ground water levels, precipitation, and evaporation. Based on the spatial relationship, the attribute information within each layer could be assigned to the specific fields (Balstrøm et al., 2006; Wise, 2014).

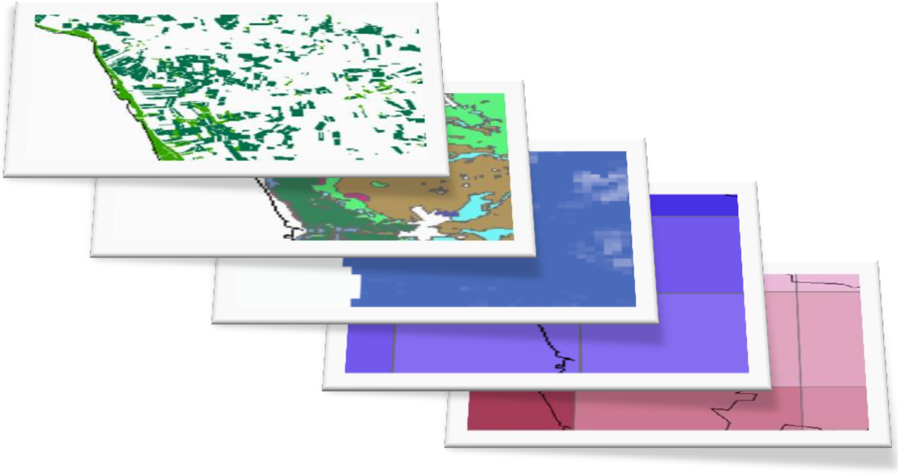


Figure 7 Stacking of different layers with geo-data in GIS.

3.1.4. GIS IN THIS THESIS

In this study the main application of GIS has been for mapping the concerned biomass resources in order to estimate the biomass potentials available for bioenergy production. GIS has furthermore been used to address the spatial distribution of the resources in relation to conversion facilities. The detail level of the analysis conducted in this study spans from the parishes of Denmark (church territorial units) to the member states of the European Union. Based on the collection of a wide range of different data types, GIS has been used directly for mapping and visualizing the distribution of the biomass resources, but also for conducting spatial analyses. The results from the spatial analyses were applied as inputs for investigating i.e. the productivity of the areas of interest and the supply chains of the biomass resources. Based on this the biomass yield potentials and the energy balance of utilizing the biomasses for biogas production could be estimated. An overview of the application pathways of GIS in this study is presented in figure 8.

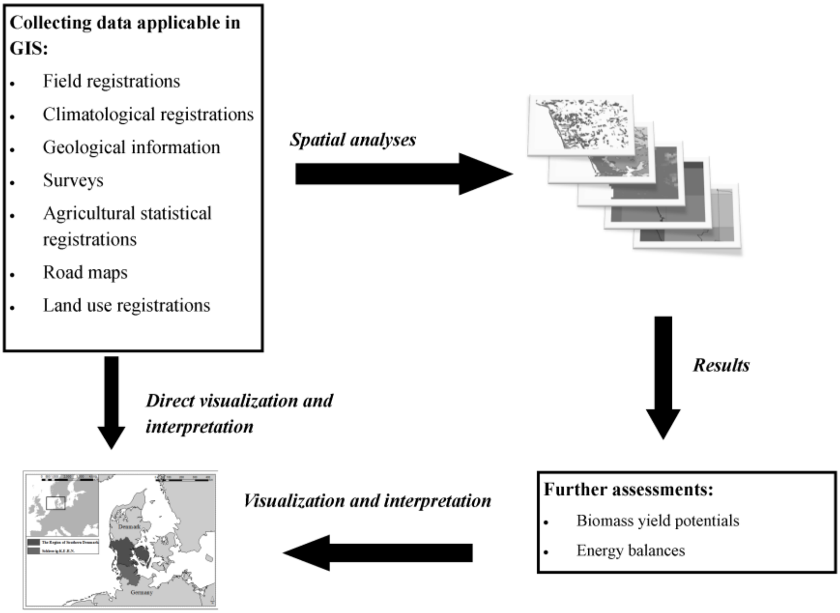


Figure 8 The application pathways of GIS in this study

A range of different geo-datasets, statistical data, surveys and analysis tools were applied depending on the specific aims of the assessments. The comprehensive descriptions of the data and analyses applied in this thesis are presented in the respective research papers.

3.2. IDENTIFICATION OF SUSTAINABLE BIOMASSES

As presented in the previous chapters, sustainability is of key significance in the use of biomass feedstock for energy production. In the Brundtland report from 1987 sustainable development is defined as a“…development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987). The term sustainability however is used in many different disciplines and contexts, thus the interpretation of sustainability varies. In the field of population biology, sustainability is often defined as the carrying capacity, meaning the maximum population size that the environment can support on a continuous basis. In economy sustainability is often defined as the avoidance of actions which reduce the long-run productive capabilities of the natural and environmental resource base (Field & Field, 2006). Some interpretations of sustainability argue that the use of a resource is sustainable, if the value of the resource being depleted is matched by capital investments of equal value in other natural resources or in productive non-resource capital (Field, 2001). Yet the complexity of the ecosystem services providing these resources, and the lacking of a full understanding of the direct and indirect consequences of the overuse or depletion of a resource within an ecosystem makes it questionable if such investments are sufficient to actually sustain the long-run productive capabilities of the natural and environmental resource base.

As bioenergy production requires the direct use of ecosystems services, assessing the sustainability of biomass use and bioenergy production is complex, but highly needed. Sustainable use of biomass resources are however essential for a stable long term bioenergy supply. The cultivation of fast growing and high yielding energy crops appears to be a quick and relatively easy way of supplying the bioenergy sector with renewable feedstock and thus reduce the emissions of greenhouse gases. However it can also generate negative externalities in our societies and ecosystems limiting the possibilities for the future development. In contrast, positive externalities can be obtained by the energetic utilisation of other biomass feedstock i.e. organic residuals, when planning the acquisition and utilisation processes carefully.

On European level, sustainability of the biomasses used for bioenergy production has received increasingly attention. In order to ensure a more sustainable production, the EU directive on promotion of the use of energy from renewable sources has defined sustainability criteria for biofuels. For the use of solid and gaseous biomass sources in electricity, heating and cooling only a set of non-binding recommendations for the ensuring the sustainability has been set (European Commission, 2014):

I. The biomass use should ensure greenhouse gas savings of at least 35% compared to fossil fuels (increasing to 50% in 2017, and 60% in 2018 for new plants).

II. Resources cultivated on areas converted from land with high carbon stocks and land with high biodiversity should not be used.

None of the recommendation takes into account that biomass production on farmland both directly and indirectly could contribute to crossing the planetary boundaries even further, due to e.g. extensive fertilisation, fresh water use, soil erosion. Nor do they consider the issue of food production being replaced by energy crop production on the arable farmland, reducing the food supply.

3.2.1. SUSTAINABILITY CRITERIA

In order to identify biomass resources that hold a potential of being utilised with a minimum risk of negative externalities or potentially generation positive externalities, a set of more comprehensive sustainability criteria was developed and applied. These criteria formed the framework for selecting the biomass resources which have been investigated in this thesis, as illustrated in figure 9.

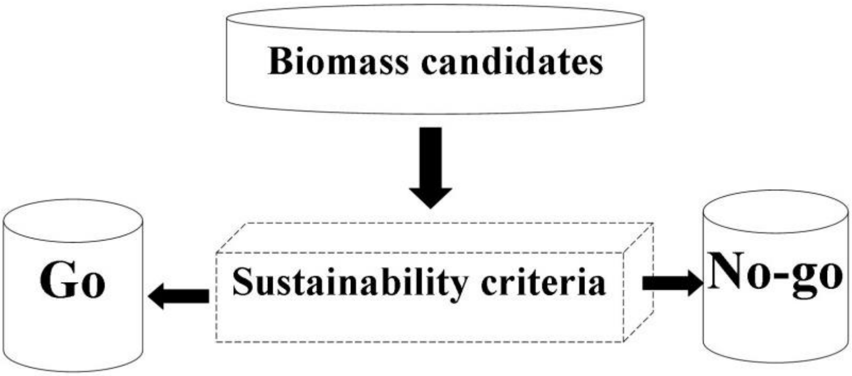


Figure 9: Simplified process of the identification of sustainable biomass resources

The criteria represent what is considered to be the most significant measures related to sustainable biomass use within the extent of the geographical research area. Thus, they should not be regarded as an exhaustive set of sustainability criteria, due to the complexity of the ecosystems and the diversity of local societies.

In order to assess the sustainability, a general categorization of the biomasses was made, differentiating between whether the exploitation of the biomass directly or indirectly requires the utilisation of land:

- *Biomass resources requiring direct land use:* Biomasses intended for bioenergy production cultivated or acquired by direct land use.
- *Biomass resources indirectly requiring land use:* Biomasses which are residuals from a process or system that requires direct land use. The primary cause for land use is thus related to the specific process/system and only indirectly to bioenergy production.

This categorization was made in order to be able to differentiate whether the utilisation of a biomass resource for bioenergy production is directly responsible for potential positive or negative impacts, or if such impacts are caused due to other primary aims related to the use of land.

The sustainability of the biomass resources was assessed differently according to which category they belong to as presented in the next two sections.

3.2.1.1 Criteria for biomass resources requiring direct land use

The sustainability of the use of biomass resources requiring direct land use was assessed by developing a set of criteria. The biomasses were evaluated in respect to these criteria in order to determine if the use of the biomass is sustainable.

The applied criteria for identifying and selecting sustainable primary biomass resources for further research in this study are presented below.

Renewability

- If cultivated on agricultural land the concerned biomass resource should be within a system where the regrowth of plant material is the normal practice.
- If the concerned biomass derives from uncultivated natural areas, the exploitation should allow for the natural species to regrow.

Food supply

- Production of the concerned biomass should not replace the production of feed and food crops.
- Food and feed crops should only be used for bioenergy production if they are considered as a residue due to i.e. poor nutritional value.

Ecosystem impacts

- Negative impacts on the ecosystems due to the acquisition or cultivation of biomass resources should be avoided.

Land use changes

- No negative direct or indirect land use changes should be generated due to the production/acquisition of the concerned biomass resource.

3.2.1.2 Criteria for biomass resources indirectly requiring land use

Systems that require direct use of land while resulting in the generation of organic residues are considered to be responsible for the potential impacts that the specific system can cause on the criteria listed in the previous section (3.2.1.1). If the use of the residues does not impact the range of land use needed in the system, it can be argued that the residue is not responsible for impacts on the listed criteria. The use of residues from such systems is therefore considered to be sustainable in respect to the listed criteria, as they have no direct impact on them.

If the residues can be, or already are, used for other purposes, it should however be considered if unavailability for such purposes results in other unsustainable effects.

Based on this, a criterion for the use of organic residues to be sustainable was defined:

- The use of organic residues for energetic purposes should not reduce or restrict the possibilities of using the residues for other essential purposes.

3.3. AVAILABILITY ASSESSMENT

The availability of the identified biomass resources was another aspect assessed in this thesis. The availability of sustainable biomass resources is of significant relevance for the biogas sector. The use of a biomass resource can be defined a sustainable, but in order to contribute to the production of renewable energy, it is of relevance that the resource is present in considerable quantities within the geographical area of interest.

The main factors influencing the availability of the biomass resources were identified to be:

- The spatial distribution of the resource
- The productivity of the resource
- The acquisition process and management of the resource
- The existing demand/use of the resource for food and feed production
- The existing demand/use of the resource for other bioenergy production facilities.

As illustrated in figure 10, each of these factors again depends on several aspects, which were further investigated in the specific research areas by using a combination of different methods i.e. spatial analyses, statistical analysis, literature studies, field studies, laboratory experiments. The specific details regarding the application of these methods and the used materials and data are presented in the respective research papers.

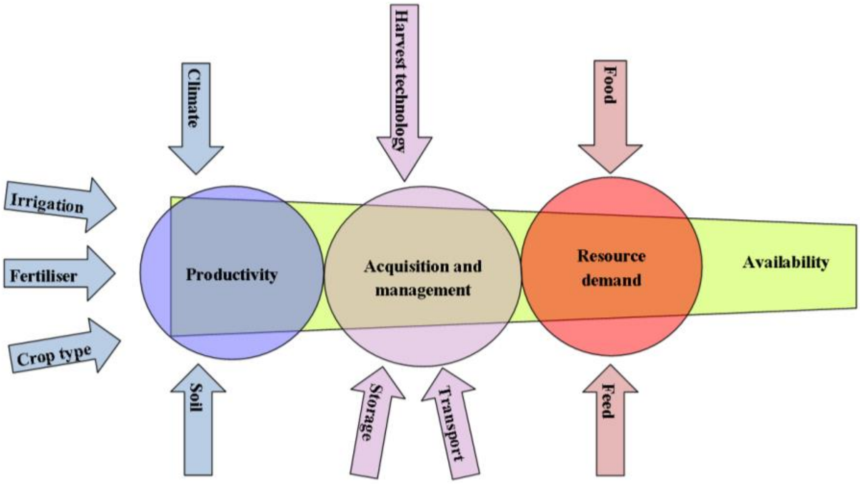


Figure 10: The main factors influencing the availability of the biomass resources.

3.4. ENERGETIC FEASIBILITY ASSESSMENT

Energetic feasibility of utilising the identified biomass resources is an essential criterion in the context of sustainability. Sustainability is important when choosing a biomass resource for utilisation; however a sustainable utilisation process is also a critical aspect. In this context, the energetic feasibility has been investigated for part of the biomass resources assessed in this study. This was done by comparing the energy requirements for obtaining the biomass resources (energy inputs) to the energy yields that can be obtained by utilising them for energy production (energy outputs).

The energy inputs and outputs depend on several different factors, as exemplified in figure 11. In order to estimate the energy balance these factors were investigated in the specific research areas by using a combination of different methods i.e. spatial analyses, statistical analysis, literature studies, field studies, laboratory experiments. The specific details regarding the application of these methods and the used materials and data are presented in the respective research papers.

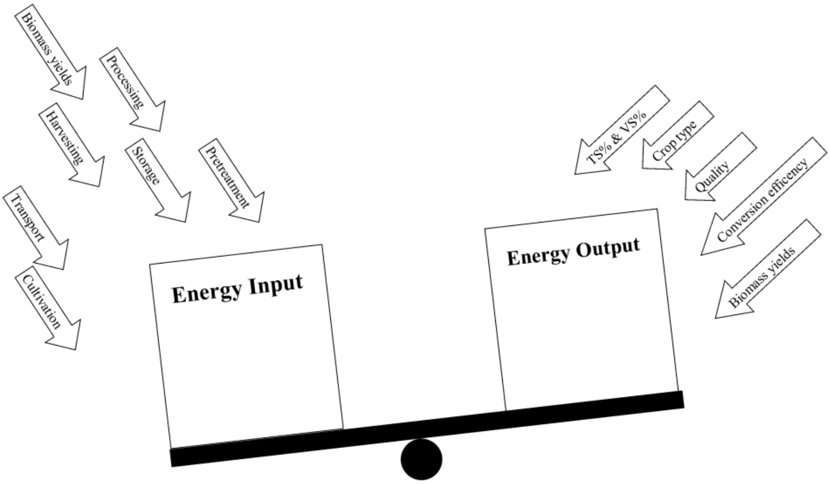
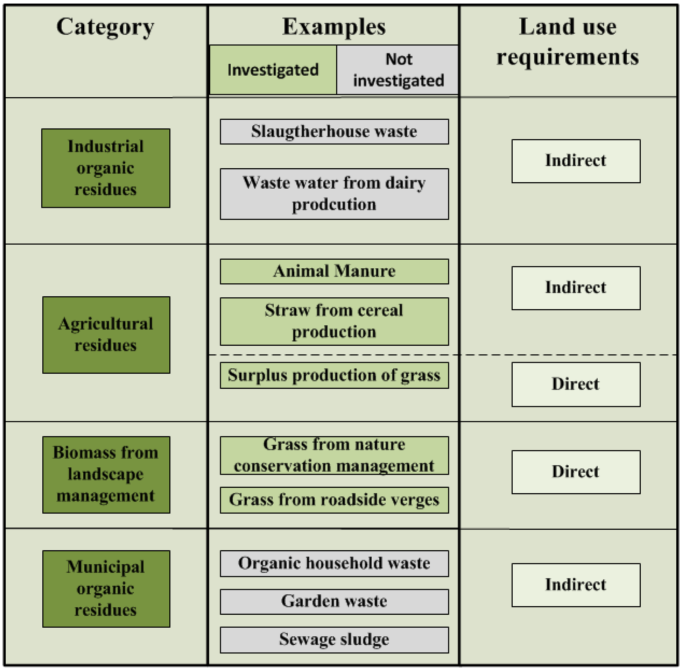


Figure 11: The energy inputs and outputs depend on several different factors.

4 PAPERS PRELUDE

The general objective of this thesis work was to identify, map and investigate possible biomass resources for sustainable bioenergy production. A combination of literature studies and empirical experiences were applied in order to identify which biomass resources that fit into the framework of sustainability in this study. Four main categories of sustainable biomass resources were identified, as illustrated in figure 12.

Several examples of biomasses were identified to fit within the different categories, but the biomasses designated for further research within this study were narrowed down to be: animal manure, straw, surplus grass from agricultural production, grass from nature conservation, and grass from roadside verges. Thus, the selected biomass types represent resources which are already commonly used in bioenergy production, so as they also represent more novel substrates for bioenergy production



Category	Examples		Land use requirements
	Investigated	Not investigated	
Industrial organic residues		Slaugtherhouse waste Waste water from dairy prodcution	Indirect
Agricultural residues	Animal Manure Straw from cereal production		Indirect
	Surplus production of grass		Direct
Biomass from landscape management	Grass from nature conservation management Grass from roadside verges		Direct
Municipal organic residues		Organic household waste Garden waste Sewage sludge	Indirect

Figure 12: The main categories and examples of biomass resources identified as sustainable.

The papers elaborated in this PhD study relates to the selected biomass resources which have been assessed according to the overall research approach on different geographical levels, as presented in table II.

Table II: The geographical extent and applied key assessments of the papers.

Paper	Topic	Geographical extent	Key assessments		
			Sustainability	Availability	Energetic feasibility
1	Roadside grass	Denmark	✔	✔	✔
2	Surplus grass	The region of Southern Denmark	✔	✔	
3	Nature conservation grass	Denmark	✔	✔	✔
4	Manure, straw & surplus grass	Europe	✔	✔	

Four different research papers were elaborated in the framework this PhD period. A brief introduction and an abstract of the research papers will be given in the following sections, whereas key findings from each topic, in respect to the assessments of sustainability, availability and energetic feasibility, is presented in chapter 5-8.

.

Paper 1

Title: Bioenergy production from roadside grass: A case study of the feasibility of using roadside grass for biogas production in Denmark

Authors: Ane Katharina Paarup Meyer, Ehiaze Augustine Ehimen, Jens Bo Holm-Nielsen.

Status: Published in Resources, Conservation and Recycling 93 (2014) 124–133 http://dx.doi.org/10.1016/j.resconrec.2014.10.003

Abstract: This paper presents a study of the feasibility of utilising roadside vegetation for biogas production in Denmark. The potential biomass yield, methane yields, and the energy balances of using roadside grass for biogas production was investigated based on spatial analysis. The results show that the potential annual yield of biomass obtainable from roadside verges varies widely depending on the local conditions. The net energy gain (NEG) from harvest, collection, transport, storage and digestion of roadside vegetation was estimated to range from 60,126–121,476 GJ, corresponding to 1.5–3.0% of the present national energy production based on biogas. The estimated values for the energy return on invested energy (EROEI) was found to range from 2.17 to 2.88. The measured contents of heavy metals in the roadside vegetation was seen not to exceed the legislative levels for what can be applied as fertilizer on agricultural land, neither does it reach levels considered as inhibitory for the anaerobic fermentation process. From a practical point of view, few challenges were identified related to the acquisition and processing of the roadside vegetation. Considering the positive net energy gains, further energy investments for management of these challenges can be made. Despite the somewhat low EROEI values, the use of this resource could however result in other positive externalities, such as improved biodiversity of the verges and recycling of nutrients.

Paper 2

Title: The potential of surplus grass production as co-substrate for anaerobic digestion: A case study in the Region of Southern Denmark

Authors: Ane Katharina Paarup Meyer, Caroline Schleier, Hans-Peter Piorr, Jens Bo Holm-Nielsen.

Status: Accepted for publication in Renewable Agriculture and Food Systems, July 20th 2015.

http://dx.doi.org/10.1017/S1742170515000277

Abstract: This paper presents an assessment of the surplus grass production in the Region of Southern Denmark, and the perspectives of utilising it in local biogas production. Grass production represents a significant role in the Danish agricultural sector. However, statistical data shows an excess production of averagely 12% in the period 2006-2012. Based on spatial analyses and statistical data, the geographical distribution of grass production and consumption was estimated and mapped for the Region of Southern Denmark. An excess production of grass was estimated for several of the municipalities in the Region of Southern Denmark, but the excess production were found to be quite sensitive to the management practice of the grass fields and the productivity of the grass. The yields of excess grass estimated in the sensitive and conservative scenario was found to be sufficient to serve a sole co-substrate in 2-8 biogas plants using animal manure as primary feedstock. The yields in the intensive scenario were assessed to be sufficient to serve a sole co-substrate in 8-16 biogas plants. Alternatively, at least 31% of the regionally produced maize which is exported to the biogas sector could annually be substituted by methane produced from the production of excess grass. The intensive scenario was estimated to have significantly higher grass yields than the sensitive and conservative scenario. The environmental impacts of intensified agricultural management should however be assessed carefully in order to ensure that the ecosystems are not increasingly being burdened. The potential of utilising residual grass for energy production in the region or as an alternative to the maize exported to Northern Germany was concluded to seem as a promising possibility for a sustainable development of the regional biogas sector. Furthermore, it could provide incentives for establishing new biogas plants in the region and thereby increase the share of manure being digested anaerobically, which could help extrapolate the environmental and climate related benefits documented for use of digested animal manure as fertiliser on agricultural land.

Paper 3

Title: The energy balance of utilising meadow grass in Danish biogas production.

Authors: Ane Katharina Paarup Meyer, Chitra S. Raju, Sergey Kucheryavskiy, Jens Bo Holm-Nielsen.

Status: Accepted for publication in Resources, Conservation and Recycling, July 26th 2015.

Abstract: This paper presents a study of the energy balance of utilising nature conservation biomass from meadow habitats in Danish biogas production. Utilisation of nature conservation grass in biogas production in Denmark represents an interesting perspective for enhancing nature conservation of the open grassland habitats, while introducing an alternative to the use of intensively cultivated energy crops as co-substrates in manure based biogas plants. The energy balance of utilising nature conservation grass was investigated by using: data collected from previous investigations on the productivity of meadow areas, different relevant geo-datasets, spatial analyses, and various statistical analyses. The results show that values for the energy return on energy invested (EROEI) ranging from 1.7 to 3.3 can be obtained when utilising meadow grasses in local biogas production. The total national net energy gain (NEG) was estimated to more than 600.000 GJ corresponding to ≈15% of the total Danish biogas production in 2012.

Paper 4

Title: The future of European biogas production – an outlook for 2030 focussing on sustainable biomass utilisation of animal manure, straw and grass.

Authors: Ane Katharina Paarup Meyer, Ehiaze Augustine Ehimen, Jens Bo Holm-Nielsen.

Status: Submitted to Fuels, June 2015.

Abstract: Biogas is a diverse energy source, suitable as a flexible and storable energy form. In the European Union (EU), biogas is expected to play an important role in reaching the energy policy targets. The sustainability of substrates used for biogas production has however been under a critical discussion. The aim of this study was to project and map the potentials of sustainable biomasses in 2030 in the EU. The investigated types of residual biomass were animal manure, straw from cereal production, and excess grass from both rotational and permanent grasslands and meadows. In total the energy potential from the investigated resources was projected to range from 39.3-66.9 Mtoe, depending on the availability of the residues. In the perspectives of the energy political targets, the projected energy potential could cover 2.3-3.9% of the total EU energy consumption in 2030 or 8.4-14.3% of the total supply of renewables in 2030

.

5 GRASS FROM ROADSIDE VERGES IN DENMARK

In Denmark, roadside verges are usually mowed twice a year: spring/early summer and autumn. The verges are mowed for several reasons: to maintain visibility of signs and traffic equipment, to provide verges that can act as refuges/habitats and corridors for wild flora and fauna, to ensure that there is a clear overview through curves and connected roads, to prevent rain water flooding the roads, and to ensure that the roadsides are in a condition that they can be used as emergency lanes in case a vehicle has to stop. The harvested roadside grass is usually left as a vegetative cover layer on the roadsides areas, where it is allowed to decompose. Instead of leaving the harvested roadside grass to decompose on the verges, it could be used for biogas production.

Investigations and reports on the use of vegetation sourced from roadside verges were found to be quite limited, with roadside biomass research mainly concentrated on its use to monitor and evaluate heavy metals and organic pollutants emanating from road transport (Ho & Tai, 1988; Garcia & Millán, 1998). However a few European reports and papers on this topic were identified having quite different views and conclusions related to the possibilities of utilising roadside vegetation for bioenergy production (Pick et al., 2012; Delafield, 2006; Salter et al., 2007; Qin, 2011)

Pick et al. (2012) concluded that the utilisation of roadside grass in biogas plants in Schwäbisch Hall County, Germany, was unfavourable due to high costs, associated with the biomass harvest and collection, and the potential content of pollutants and waste in the roadside vegetation.

In Sweden, Durling and Jacobsen (2000) conducted a study assessing the energy consumption and the costs per tonne of roadside grass when used for anaerobic digestion, composting, or combustion. The results show that anaerobic digestion and combustion of the roadside vegetation gives a positive net energy production, indicating that the utilisation is feasible from an energetic point of view.

In the region of Powys, Wales, the “Living Highways Project” (Delafield, 2006) conducted trials harvesting roadside vegetation with a specialised harvesting machine. The harvest machinery was evaluated to work effectively and no concerns related to waste in the harvested grass were reported. Based on the results for the harvest yields in Powys, Salter et al. (2007) set up a model to determine the energy efficiency and surplus energy yield of using roadside vegetation as feedstock for biogas production in the UK. Their results indicated that the biogas quantity produced from roadside vegetation (harvested in a radius of 20 and 45 km from a biogas plant) is sufficient to cover the energy demand for harvesting, transport and biogas production processes.

No studies of the possibilities of utilising roadside grass as a sustainable feedstock for biogas production in Denmark were however identified, thus the topic was assessed in research **paper 1**. The main findings are presented in the following sections.

5.1. SUSTAINABILITY ASSESSMENT

In order to utilise roadside grass, the roadside verges must be harvested and the grass collected. The removal of the grass clippings has been found to impact the biological diversity of the verges positively (Noordijk et al., 2009; Parr & Way, 1988), but the removal does not directly hinder regrowth of the vegetation in the verges. However, an issue rarely considered, which could impact the regrowth of the vegetation is the fact that the removal of grass cuttings from roadside verges implies removal of nutrients in the plant biomass. It is therefore not clear (given the current management strategy) how nutrients being taken out will be made available for the regrowth of roadside grasses. However, verges adjacent to agricultural land could be subjected to nutrient flow from fertilisation on the agricultural land, but it is uncertain to what extend this happens and how much it impacts the biomass yields. Despite that the composition of plant species may change due to changes in the soil concentration of nutrients, roadside grass is however still considered to be a *renewable* resource, as regrowth of plant vegetation is not hindered by the harvest and removal.

The utilisation of the grass does also not impact *food production*, as the roadside verges currently represent unutilised areas in regards to food or feed production. The use of roadside vegetation was found not to negatively impact the *ecosystems*. On the contrary, studies have found that the harvest and removal of roadside grass created positive impacts in the flora and fauna of the roadsides (Noordijk et al., 2009; Parr & Way, 1988) by increasing the species richness. Thus, the use of roadside grass could help maintaining the functioning of the ecosystems. No negative *direct or indirect land use changes* were identified to be generated by the acquisition of roadside grass, as the primary land use of the verges remains.

5.2. AVAILABILITY ASSESSMENT

The availability of roadside grass was investigated for Denmark by carrying out field and laboratory experiments, spatial analysis, and literature review.

A spatial analysis was carried out in order to estimate the distribution and quantity of the roadsides in Denmark by using the geographical information mapping system Esri ® ArcMap 10.1 and road maps from the OpenStreetMap © contributors (2015).

In order to assess the potential obtainable grass yields, roadside grass was collected during two sampling periods; May 2012 and in October 2012. Stripes of approximately 1 m width and 4 m length were harvested in both periods (dictated by the current management strategy for the spring season) from different road types in order to have a comparable basis. The collected grass was analysed in the laboratory in order to assess the content of total solids and total volatile solids.

Yields ranging from 1.50 – 6.25 t fresh grass per hectare annually were obtained from the sampled roadsides in Denmark. The total solids content varied from 18.6-28.4 g TS/g fresh grass, and the total volatile solids content ranged from 76,6-93,9 g VS/g TS. The highest biomass yields were seen for October. This could be expected as the vegetation has had better growth conditions in the summer period (from the first harvest in May to the second harvest in October), compared to the winter period (spanning from the autumn harvest in the year before to May in 2012).

In the literature, yields of total solids per hectare of roadside verge were found to be 60% and 40% higher in respectively Germany and Wales (Delafield, 2006; Kern et al., 2009), compared to the average yields found for Denmark. The achievable yields will vary depending on time of harvest, soil conditions, weather, and the dominating vegetation of the verges. However, only few locations from the case study in the region of Southern Denmark showed yields in the range of those identified for Germany.

The road network with harvestable verges in Denmark was estimated to represent 34,983 km. The distribution of the road network and biogas plants in Demark is illustrated in figure 13. Depending on the harvestable width of the verges, it was estimated that an area of 15,754-25,187 ha could be utilised for biomass acquisition in Denmark. This corresponds to an annual yield of total solids ranging from 18,727-29,946 t.

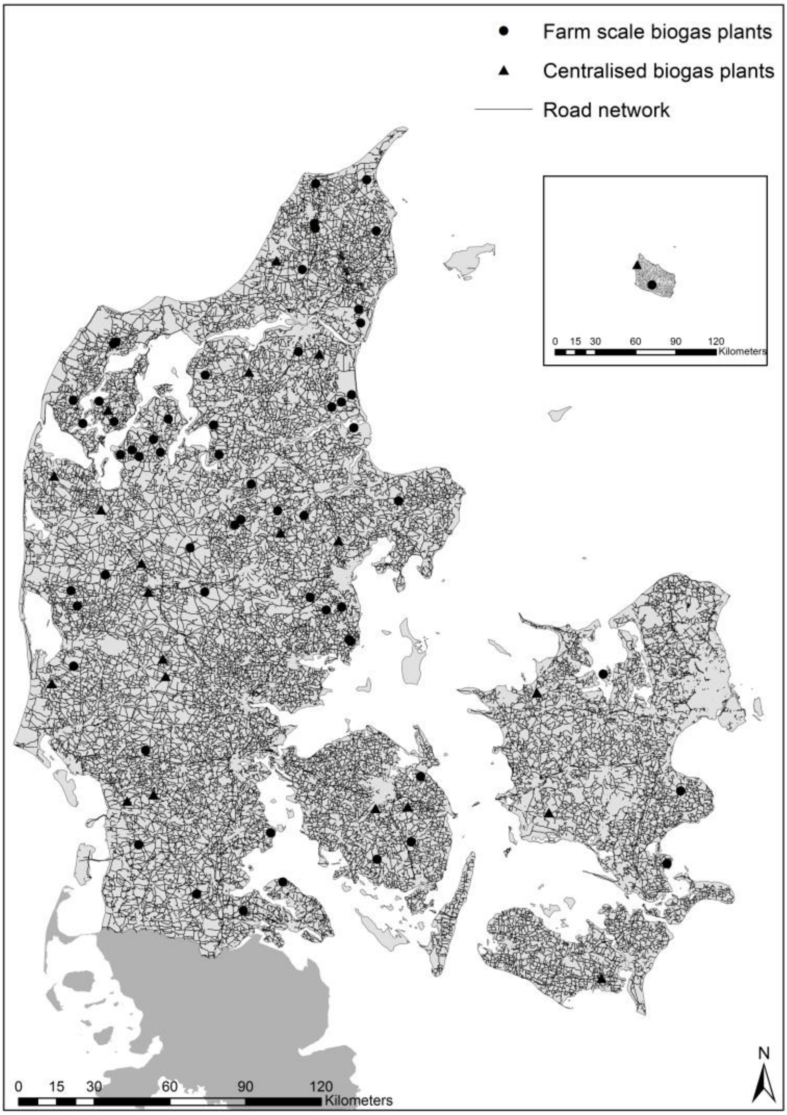


Figure 13 The distribution of the road network and biogas plants in Demark

5.3. ENERGETIC FEASIBILITY

The energetic feasibility of utilizing roadside grass for biogas production in Denmark, was assessed by estimating the annual net energy gain (NEG) and the energy return on energy invested (EROEI) (Hall et al., 2009; Arodudu et al., 2013).

All values used for estimating the energy requirements for the practical management of acquisition and processing of road-side vegetation, were derived from the literature. The energetic feasibility was investigated for three cases in order to reflect the different possibilities for the end use of the roadside grass:

Case I. only the farm scale biogas plants in Denmark will receive the harvested grass.

Case II. only the centralised scale biogas plants in Denmark will receive the harvested grass.

Case III. both farm scale and centralised biogas plants in Denmark will receive the harvested grass.

By carrying out a buffer analysis by using the geographical information system the buffer radius around the biogas plants needed for full coverage of the road network in Denmark were identified as illustrated in figure 14. The results from the buffer analysis were applied for estimating the transport distances of the roadside grass.

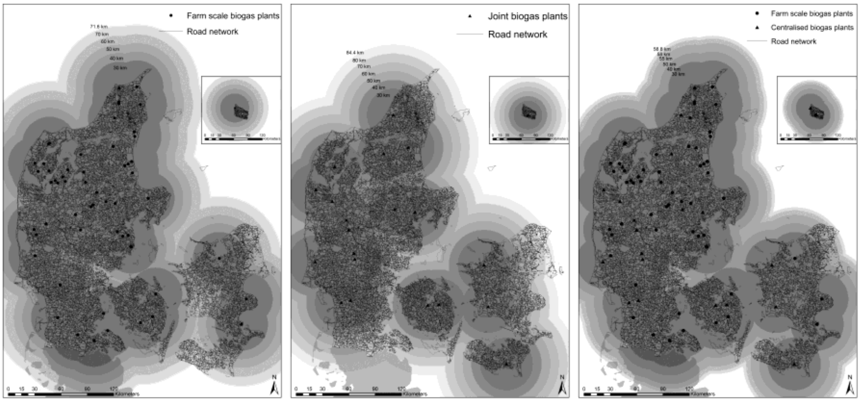


Figure 14 Buffer analysis assessing the radii of the buffers needed around the biogas plants in order to fully cover the road network.

With the aim of estimating the required energy input for utilising roadside grass in biogas production, the processes were divided into the sub steps:

- Harvesting and collection in containers
- Loading of containers containing grass on trucks
- Transport of the containers to a biogas facility
- Offloading of the containers from the truck and emptying its content
- Storage in silage tubes at the biogas plant

In order to estimate the energy output from anaerobic digestion of roadside grass, the theoretical methane yields from the roadside grass samples were assessed in the laboratory by using the method put forward by Boyle (1977) and compared to studies on the practically obtainable methane yields from grass. Before estimating the final energy output from roadside grass use, part of the potential methane production was allocated to the operation of the biogas plants (heat and electricity), and the transportation of the digested organic material.

Case I (only farm scale biogas plants receive the harvested grass) showed the lowest values for the NEG, ranging from 60,126-101,454 GJ. The EROEI, however, was estimated to range 2.17-2.88, representing both the lowest and highest value for the energy return on energy invested.

Case II (only the centralised biogas plants receiving the harvested grass) showed the highest NEG, ranging from 81,415- 121,476GJ, while the EROEI was estimated to be 2.39-2.84.

For case III (both farm scale and centralised biogas plants receiving the harvested grass), the NEG was estimated to range from 68,345- 114,597 GJ, while the EROEI was estimated to 2.35 - 2.81.

The results shows that net energy gains can be achieved using grass harvested from roadsides for biogas production. The energy return on invested energy is above 2 for all investigated cases, thus utilisation of roadside grass in biogas production in Denmark could be feasible from an energetic point of view. The net energy gain (NEG) from harvest, collection, transport, storage and digestion of roadside vegetation corresponds to 1.5–3.0% of the present national energy production based on biogas.

As the roadsides in Denmark are already mowed up to two times annually to ensure traffic safety it can be argued if the energy consumed for conducting the current management practices ought to be included in the energy balance. This argument can be viewed as a matter of what the principal aim of roadside mowing is for. Is it to facilitate traffic safety or for biomass production for energy? The energy requirements for the harvest and collection of the roadside grass on average represent 70% of the total energy input. Estimating the energy balance, considering only the additional energy requirements after the current management practices (which are done to facilitate traffic safety only) would result in considerably higher NEG and EREOI. This would favour the use of roadside grass for biogas production in the final results.

6 EXCESS PRODUCTION OF GRASS IN THE REGION OF SOUTHERN DENMARK

Grass production represents a significant role in the Danish agricultural sector. Twenty percent of the total agricultural land in Denmark is cultivated with grasses or designated as permanent grassland (Statbank Denmark, 2015a). The main purpose of grass production is to supply the ruminant livestock industry with high quality forage, due to a large production of dairy products (5 million tons in 2013 (Statbank Denmark, 2015b)). A comparison of statistical data showing the annual consumption of grass for livestock production, and the annual grass production (harvested grass), however shows an excess production of averagely 12% of the total grass production in the period 2006-2012 (Statbank Denmark, 2015c; Statbank Denmark, 2015d). The reasons for the production of surplus grass could not be documented. Potential reasons could however be that the main consumer of grass, the Danish livestock production, decreased by 24% in the period 1995-2013 (Eurostat, 2015e), and low forage value of part of the grass due to unfavourable weather conditions or late harvest dates. Excess grass from agricultural grass production could potentially meet part of the demand for substrates for anaerobic digestion in the Region of Southern Denmark without competing with the use of land for food and feed production. Alternatively, excess production of grass could substitute part of an intensive production of maize cultivated for export to Northern Germany.

The potential and availability of surplus grass production from permanent and rotational grass land for biogas production in the region of Southern Denmark were investigated in **research paper 2**. The main findings are presented in the following sections.

6.1. SUSTAINABILITY

Grass produced on agricultural land is considered to be *a renewable resource*, as grass cultivation usually continues in the subsequent seasons either on the same field (permanent grass) or in rotational systems. Regrowth of the grass is not a certainty, but as the cultivation of grass within rotational agricultural systems creates good soil properties which can be utilised for the cultivation of crops in the subsequent seasons, grass cultivation if often an integrated part of rotational systems.

In order to avoid any negative impact on the food supply, only grass which is not used for forage should be used for energy production: Thus, grass is only considered to be *sustainable in respect to food production* if it has no use in the agricultural systems.

The potential impacts on the ecosystems caused by the production of grass depend on the management practices in the cultivation systems. As emphasized by Matson el al. (1997), agricultural intensification can have local negative consequences such as increased erosion, reduced soil fertility, and declining biodiversity; but also negative regional and global consequences such as ground water pollution, eutrophication of rivers and lakes and impacts on atmospheric constituents and climate. However, studies from Aarhus University imply that the potential link between increased nitrate leaches due to increased fertilisation can be decoupled (Sørensen, 2014). Fields cultivated with festulolium grass and fertilised with 425 kg N ha^{-1}, yielded up to 22 t TS ha^{-1}, while the nitrate leach from the fields was found to be less than on unfertilised clover grass fields. It can nevertheless be argued, that potential negative impacts on the ecosystem services caused by grass cultivation is not directly linked to the aim of producing energy, as only the excess production of forage grass is considered in this context. Thus, the potential negative impacts will be caused due to the primary aim of cultivating the land (forage production), and not due to energy production based on the grass residues. From this perspective, excess grass production is considered to be a crop that can be *utilised without causing any additional negative impacts on the ecosystems services* compared to the current situation.

Prioritising the use of excess grass production over the use of energy crops could indirectly minimise the area used for energy crop cultivation (i.e. maize). This could ease a reduction in the negative impacts associated with their intensively cultivation. *Positive indirect land use changes* could be an effect of such prioritising, if the areas currently cultivated with energy crops are replaced with crops requiring less intensive cultivation practices. *No direct land use changes* are associated with the use of excess grass production, if grass continuously is a crop integrated in the agricultural systems.

6.2. AVAILABILITY

Despite the potential for being a sustainable crop for energy production, excess grass has to be available in sufficient amounts in the region if it is to be of significance as a substrate in the local biogas production. The resource potential was therefore assessed on municipal level in the Region of Southern Denmark. A spatial analysis was performed in order locate fields with rotational and permanent grassland in the region. By overlaying the identified grass fields with maps containing information about the relevant climatological and geological characteristics, the potential obtainable biomass yields were estimated. Three scenarios were developed in order to evaluate the yields under different intensity levels of management: a sensitive, a conservative, and an intensive scenario. The regional demand for grass as forage was estimated by using registrations of the number of cattle, sheep, goats and horses. The total forage grass demand was estimated on municipal level by summarizing the demands from cattle, sheep, goats and horses for each municipality. The potential surplus production on municipal level was calculated by subtracting the demand for grass in livestock production from the gross production of grass from rotational grassland and permanent grassland production. In total, the gross grass production from these areas was estimated to range from 706,958 - 1,116,551 feed units depending on the scenario for the management strategy and variation in the obtainable grass yields.

The area of rotational and permanent grassland on municipal level is illustrated in figure 15. A high production of grass is found along the west coast of Southern Jutland.

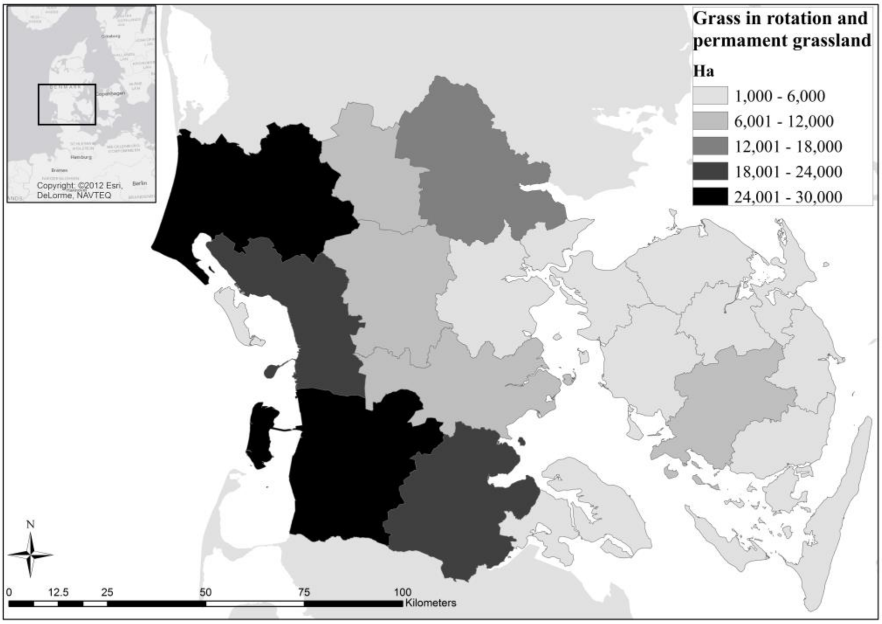


Figure 15 Hectares of rotational and permanent grassland on municipal level in the Region of Southern Denmark

The annual feed demand in terms of forage grass on municipal level is illustrated in figure 16. The highest demand for forage grass was estimated for the municipalities along the west coast of Jutland, which also were the ones found to have the largest areas of grassland. In total, the annual demand for forage grass in the Region of Southern Denmark was estimated to be ≈ 795,000 feed units, from which 94% of the demand origins from cattle production.

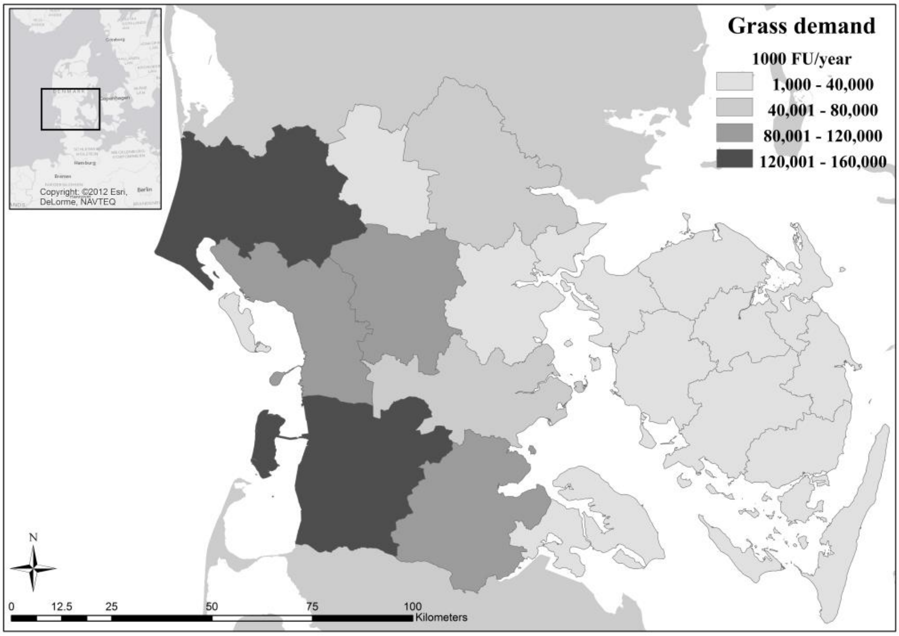


Figure 16 The annual forage grass demand per municipality in feed units per year

Figure 17 shows the number of manure based biogas plants on municipal level where the yields of excess grass could serve as co-substrate. The biogas plants are assumed to digest a total of 200,000 t biomass per year from which 18% is grass silage. In 8 municipalities there is no potential for utilising excess grass for biogas production in either of the scenarios, as the demand for forage grass exceeds the gross production of grass or the quantities of excess grass are too low to assume that they are of any significance as co-substrate. Assuming that the management strategy of grassland in the Region of Southern Denmark corresponds to the sensitive scenario, the results indicates rather limited possibilities for producing quantities of excess grass that are sufficient to fully cover the demand for co-substrates in future biogas plants. Nevertheless, seven municipalities are estimated to have an excess production which partly could serve as co-substrate for one biogas plant (covering at least 10% of the demand for co-substrate). In the conservative scenario the potential for utilising excess grass for biogas production is more significant. Two municipalities has an excess production corresponding to the full demand for co-substrate in at least one biogas plants, while six municipalities are estimated to have an excess production that partly could cover the demand for co-substrate in one biogas plant. In the intensive scenario an excess production which is sufficient to cover the full demand for co-substrate in at least two biogas plants is estimated for two municipalities. An excess production sufficient to fully cover the demand for co-substrate in at least one biogas plants was estimated for additional two municipalities. The excess production in the remaining municipalities (except one) was estimated to partly cover the demand in one biogas plant. Looking at the distribution of the potential biogas plants which could be supplied with excess grass shows that the possibilities on Funen are rather limited compared to Southern Jutland, even when assuming an intensified management strategy of the grasslands.

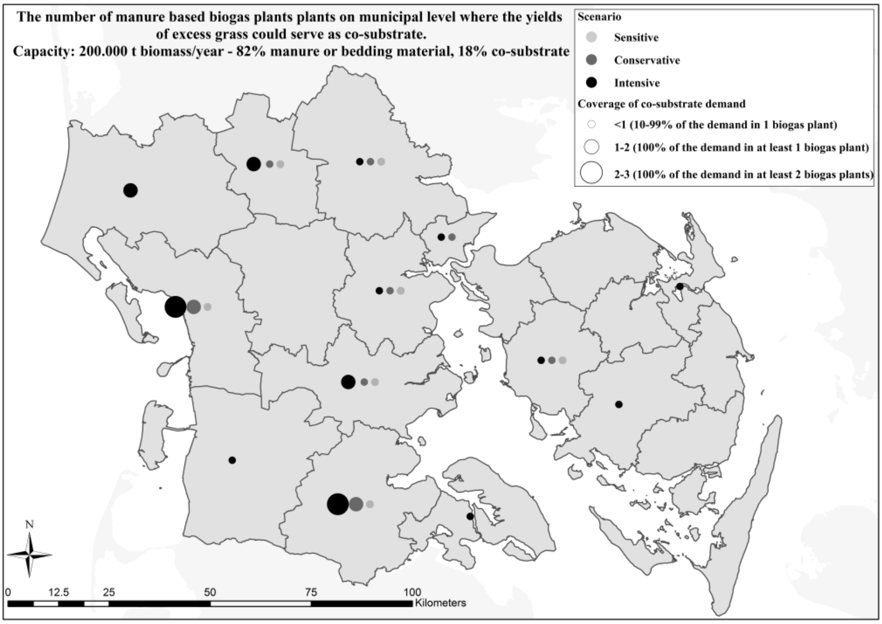


Figure 17 The number of manure based biogas plants on municipal level where the yields of excess grass could serve as co-substrate. The biogas plants are assumed to digest a total of 200,000 t biomass per year from which 18% is grass silage. The average grass yields were applied.

7 GRASS FROM NATURE CONSERVATION MANAGEMENT IN DENMARK

Grass from nature conservation and landscape management has been shown to be a suitable feedstock for anaerobic digestion (Møller & Nielsen, 2008; Jørgensen et al., 2008). The use of nature conservation grass for biogas production represents an interesting perspective for enhancing the nature conservation of the open grassland habitats, while introducing an alternative to the use of intensively cultivated energy crops as co-substrate in manure based biogas plants. The lack of nature conservation in terms of grazing or hay harvest is considered to be one of the biggest threats towards the biodiversity of the open natural and semi-natural grassland habitats in Denmark (Ejrnæs et al., 2011). Despite the habitats being protected by the Nature Conservation Act, there are no rules for continued grazing or mowing after the agricultural use has stopped (The Danish Ministry of the Environment, 2013). Due to natural succession and eutrophication, habitats which are no more mowed or grazed are in risk of changing character from having a high biodiversity with low vegetation into being overgrown by dominating tall and fast growing plant species (Ellemann et al., 2001). Without the impact from either wild ruminants or livestock production the remaining open grassland habitats cannot be maintained thus biodiversity is declining. In 2010, Ejrnæs et al. (2011) assessed the status of the biodiversity on open natural and semi-natural habitats (grassland, heather, bog and meadow). They found that the biodiversity was declining for 61-70% of the assessed elements due to overgrowth, drainage or eutrophication of the areas. The open natural and semi-natural habitats are however essential for the existence of the natural flora and fauna in Denmark, as the landscape is strongly dominated by intensive agricultural utilisation. Thus conservation of the habitats is of urgent importance.

The potential and the energetic feasibility of utilising nature conservation biomass from meadow habitats in Danish biogas production were investigated in **research paper 3**. The main findings are presented in the following sections.

7.1. SUSTAINABILITY ASSESSMENT

The utilisation of grass from meadow habitats requires that the meadow areas are harvested and collected. Well managed harvest and removal of the biomass from the areas can be considered to be a conservation method that improves or maintains the biodiversity of the habitats, as surplus nutrients are removed, and tall plant species are kept down. This creates the optimal conditions for the wide variety of plant species that belongs in the open habitats (Ejrnæs et al., 2011; Nygaard et al., 2011; Møller & Nielsen, 2008). Although the plant composition may be changed due to biomass harvest and removal, the regrowth of vegetation is not hindered, thus meadow grass is considered to be a *renewable resource*.

After the industrialization of the agricultural sector, the habitats lost their importance for livestock production as more efficient feedstock could be cultivated on the arable land. Over time majority of the natural and semi-natural grasslands were either taken out of production or drained and cultivated intensively (Buttenschøn, 2007; Nygaard et al., 2011). The habitats that have been taken out of production do no longer contribute to the production of agricultural goods, thus the use of meadow grass from such areas *will not impact food or feed production.*

Harvest and removal of the biomass on meadow habitats which are no longer used in agricultural production can be considered to be a method for conserving the nature, increasing the biodiversity of the habitats (Møller & Nielsen, 2008; Nygaard et al., 2011; Ejrnæs et al., 2011). This could contribute to *maintaining the ecosystem services* which rely on a high biodiversity. Removal of the harvested biomass implies removal of nutrients accumulated in the soil of the habitats, due to i.e. agricultural run over from fertilization of agricultural land, or imported to the habitats via flooding of nearby lakes or water streams. Harvest and removal of meadow vegetation could thus reduce the concentration of soil nutrients and minimize the potential nutrient leaching to the aquatic environment. This would further contribute to maintain or improve the nutrient balance needed to *sustain the ecosystem services*.

The energetic use of grasses growing on meadow habitats which are no longer used for agricultural production will cause a direct land use change. *The land use change is however assessed to be positive,* as it contributes to improving the biodiversity of the habitats.

7.2. AVAILABILITY

The availability of meadow grass was investigated for Denmark by carrying out spatial and statistical analyses. The spatial analysis was conducted in order to identify the location of the grassland habitats, their size, distance to both a biogas plant, and the road network. Spatial analyses was conducted by using ESRI ArcMap 10.2.1 ® software and the geo-dataset *Basemap* (Levin et al., 2012) was applied to identify the habitats defined as fresh water or coastal meadow in Denmark. The area of habitats in need for nature conservation was estimated by using an evaluation based inspections of the nature quality in subsets of the meadow habitats in Denmark conducted by the Danish state and municipalities(Nygaard et al., 2011).

A variety of statistical analyses were applied in order to investigate the potential yields of grass that can be obtained from meadow habitats, and for identifying which external and natural factors that influences the biomass yields. The analyses were carried out on a dataset consisting of field studies performed by Danish researchers, who did an extensive range of studies on the management strategies and biomass yields of meadow habitats in a period of over 20 years years (Lærke et al., 2012; L. Nielsen et al., 2002; L. Nielsen et al., 2003; L. Nielsen et al., 2012; L. Nielsen & Hald, 2008; L. Nielsen & Hald, 2010; Hald et al., 2003; K. A. Nielsen et al., 1991). Various experimental field sites located in Denmark have been investigated with respect to different factors such as geological, biological and ecological characteristics, and the various management strategies.

The total area of meadow habitats (fresh water and coastal meadows) potentially available for biomass acquisition via harvest was estimated to be ≈56,800 ha. The area of meadow habitats potentially available for biomass acquisition via harvest are mapped on a parish level (presented in figure 18). The parishes represent the geographical extent of the ecclesiastical communities in Denmark formerly used as an administrative unit, and where applied as they form the smallest geographical units in Denmark.

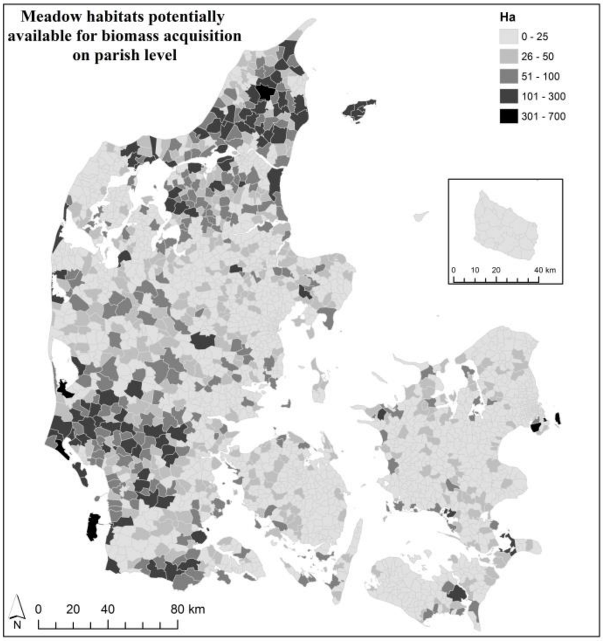


Figure 18 The distribution of meadow habitats potentially available for biomass acquisition in Denmark

The results presenting the potentially available area of meadow habitats in Denmark show that there is a significant area of meadows in Denmark which could supply the biogas sector with nature conservation grasses. It appears that the northern and south-western part of Denmark have the highest shares of meadow habitats, thus the concept of utilizing nature conservation grass for biogas production could be of high relevance in these areas. Despite a lower number of habitats in some parts of Denmark, meadow habitats are distributed all over the country, thus nature conservation grasses appear to be a resource available all over Denmark.

The obtainable biomass yields from meadow habitats were found to differ mainly depending on the management strategy in terms of number of cuts and fertilisation level. The average yields were found to be 3.8, 5.8 and 7.9 t TS/ha when conducting respectively 1, 2 and 3 cuts per year. As the nutrient concentration in the soil of the sampled habitats has not been systematically documented, the specific nutrient concentration reflected in the presented results cannot be ascertained. Several of the habitats are not currently subject to nature conservation, thus high levels of nutrients deriving from external sources (agricultural leaching) could have accumulated in the soil of the habitats. The presence of accumulated nutrients in the soil could result in high biomass yields even without additional fertilization. When removing the harvested biomass from the habitats, the nutrients are also removed, depleting the accumulated nutrients over time. It can be argued that the long term yields will decrease as the nutrients are depleted over time, if no fertilization takes place and no other external sources supply the habitats. The long term effect of nature conservation on the soil nutrient concentration is difficult to measure, nevertheless it should be considered when assessing the biomass yields.

The total obtainable yield of grass estimated for biogas plant supply areas in Denmark is presented in figure 19.

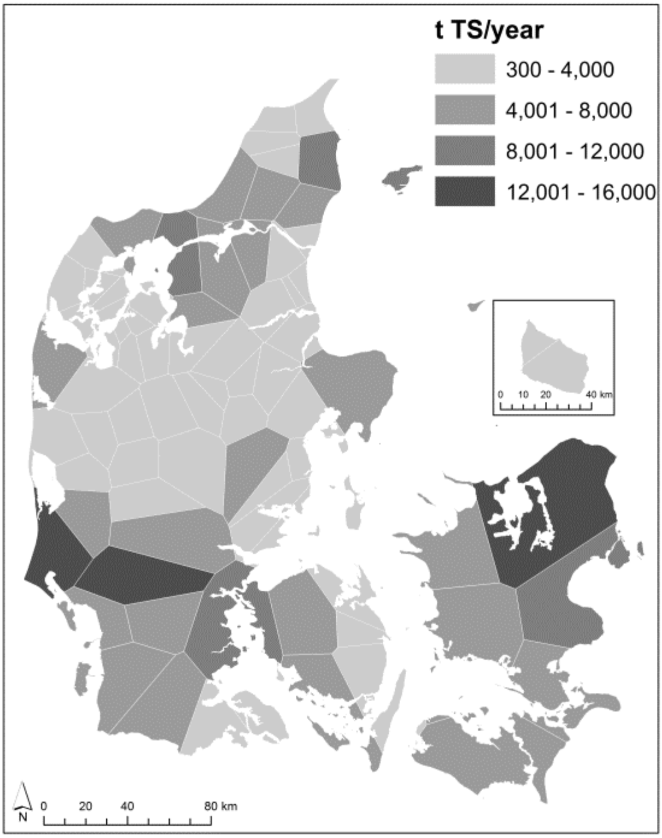


Figure 19 The annual potential biomass yield from nature conservation of meadow habitats.

In total, it is estimated that ≈310,000 t TS can be obtained from meadow habitats in Denmark. The geographical distribution of the meadow grass largely corresponds to the distribution of meadow habitats. For the majority of the supply areas the biomass yield is below 4,000 t TS indicating that the obtainable biomass yields in these areas will only play a significant role as co-substrate in small capacity farm scale biogas plants.

7.3. ENERGETIC FEASIBILITY

The annual net energy gain (NEG) and the energy return on energy invested (EROEI) (Arodudu et al., 2013; Hall et al., 2009) were estimated for the potential utilisation of nature conservation grasses in Danish biogas production plants. The NEG was calculated in GJ. The NEG and EROEI were estimated for the specific biogas plants in Denmark by identifying their potential supply areas via a spatial analysis.

For estimating the obtainable energy yields, it was assumed that the methane content in nature conservation biomass corresponds to 150 L/kg volatile solids (VS). This is in the low range of the values identified in the literature (60-309 L/kg VS (Herrmann et al., 2014), 155-293 L/kg VS (Prochnow et al., 2005)). The biomass quality and thereby the methane yield is highly influenced by the time of harvest. McEniry & O'Kiely (2013) found that advancing harvest dates negatively impacts CH_4 yields of grass. As the main purpose of harvesting the habitats is the improvement of the biodiversity, the harvest time should be planned according to that. As dry matter losses under acquisition and storage are unavoidable, 25% of the total yield of total solids was deducted before estimating the obtainable methane end energy yields (Livestock Knowledge Transfer Management Team, 2001).

In order to estimate the energy consumption for utilizing nature conservation grasses in biogas production the energy requirements for the following processes were estimated:

- Harvest and collection
- Transport of harvest machinery
- Baling of the grass
- Loading to tractor
- Transport to road
- Offloading from tractor and loading to truck
- Transport to a biogas plant
- Offloading from truck
- Pre-treatment
- Feeding to digester
- Operation of the biogas plant and management of the digestate
- Fertilisation with digestate

The annual NEG estimated for the biogas plants supply areas were found to vary from ≈700 – 40.000 GJ as illustrated in figure 20. The largest NEG values were estimated in the supply areas from which large quantities of biomass can be obtained, similar to the spatial pattern in figure18 and 19. Majority of the supply areas have an NEG below 10,000 GJ, however these supply areas are considerably smaller compared to the supply areas with higher values for the NEG.

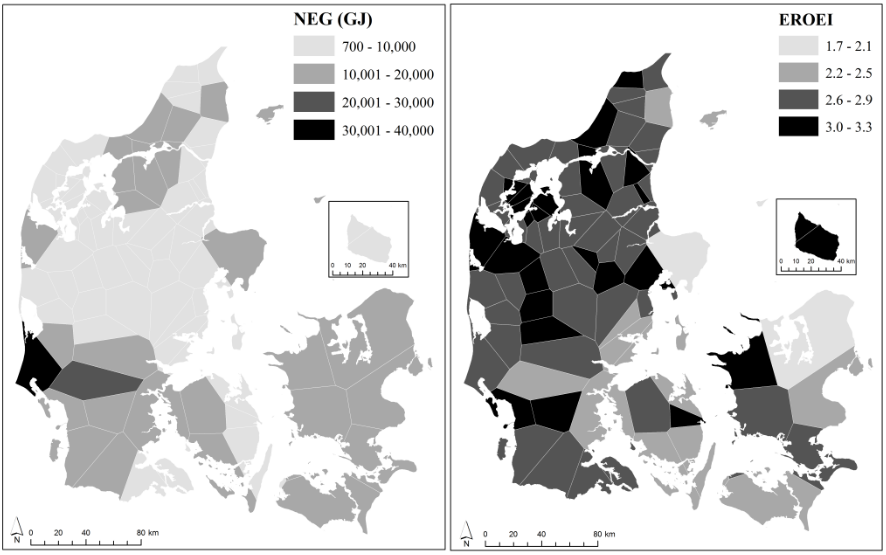


Figure 20 The illustration shows the annual NEG and EROEI of utilising nature conservation biomass from meadows in Danish biogas production on short term time perspectives, where productivity of the meadows are influenced by high concentrations of soil nutrients.

The EROEI estimated for the biogas plants supply areas were found to vary from 1.7 – 3.3. The map showing the EROEI values presents a very different picture. Despite majority of the supply areas having small values for the NEG, their values for the ERIOE are in the high range of the scale (3.0-3.3). For majority of the biogas plants the EROEI is above 2 indicating that the energy investments for acquiring the grass via nature conservation is fully covered by the energy gains from anaerobic digestion of the grass. Despite the values for the EROEI being low compared to other energy sources (Arodudu et al., 2013; Hall et al., 2009) a net energy gain of more than 600,000 GJ can be obtained on national level while creating better conditions for the biodiversity of the meadow habitats. The energy investment for harvesting the meadow habitats is thereby fully covered and an energy surplus corresponding to ≈15% of the total Danish production of biogas in 2012 (The Danish Energy Agency, 2014) can be obtained. As the aim of harvesting the biomass is to conserve nature, the removed biomass can be considered a by-product from this process. Thus it can be argued if the energy investments of conducting nature conservation should be fully designated to the aim of producing biogas. The harvesting processes alone were estimated to represent 35% of the total energy input. Estimating the energy balance, considering only the remaining energy inputs, would increase the EROEI and NEG values. This would favour the use of nature conservation grass for biogas production in the final results.

8 ANIMAL MANURE, SURPLUS GRASS AND STRAW IN THE EUROPEAN UNION

In 2013, the European Union biogas sector produced 13.5 Mtoe (Eurostat, 2015d). A further development of the biogas sector requires that the biogas production infrastructure in countries with low productivity is developed, but also that new sustainable substrates for digestion are to be introduced and documented. A supply of new substrates for a growing European biogas sector should be carefully considered in order to ensure that the biogas production is sustainable in respect to potential impacts in the environment, nature and climate. If the major part of biogas production is based on sustainable biomass sources, the EU can create a very consistent and sustainable bioenergy platform, providing the consolidated basis for reaching future political goals for the production of renewable energy and reductions of GHG emissions.

In paper 4, the potential of cattle, pig, and poultry manure, straw and surplus grass available for biogas production was projected for year 2030 and mapped for the member states in the European Union. The main findings are presented in the following sections.

8.1. SUSTAINABILITY

Animal manure is a source of nutrients which can be used for fertilising arable land. Anaerobic digestion of animal manure does however not reduce the amount of nutrients in the digestate available for crop fertilisation. In fact the fertiliser characteristics of the digestate are improved compared to raw manure. If the manure is redistributed as fertiliser to arable land, it can improve the crop production and help avoid e.g. nutrient leaching, ammonia evaporation and pathogen contamination (Holm-Nielsen et al., 2009). The use of animal manure in anaerobic digestion plants is therefore considered to be strongly sustainable as it can help minimising potential negative impacts caused by agricultural production.

As presented in section 4.2.1, the use of excess grass from agricultural production is considered to be sustainable if only grass which is not used for forage is used for energy production.

The straw residuals from the production of cereal are often considered an agricultural by-product. The nutritional value in straw is low and thus not considered a suitable livestock feedstock; hence the straw is often left in the fields for increasing the soil carbon stock. Minor applications of straw can be for livestock housing and bedding material, or in horticultural applications. Straw not used for such purposes are evaluated to represent a sustainable resource for energy production.

8.2. AVAILABILITY

For estimating the manure potential in the European Union, registrations from 2013 of the number of animal heads of cattle and pigs from Eurostat were applied as base values (Eurostat, 2015f; Eurostat, 2015g). For poultry, the number of slaughtered animals registered by Eurostat was used (Eurostat, 2015h). The amounts of produced animal manure were estimated based on the standards from the American Society of Agricultural Engineers (2005).For estimating the amount of animal manure available for biogas production, it was assumed that only 50% of the cattle manure can be collected (considering the housing period), whereas it was assumed that 90% of the manure from pigs and poultry can be collected as conventional farming methods usually imply that the animals are housed during most of their lifetime.

The potential of surplus grass from rotational and permanent grassland was estimated based on registrations from Eurostat. The total production was estimated by assuming yield levels ranging from 10-14 t TS/ha for rotational grassland and 2-4 t TS/ha for permanent grassland. The actual grass yields obtainable from grassland areas must however be expected to vary according to the climate-conditions (Smit et al., 2008), so as the soil type and management practices also influence the obtainable yields of grass. In the case of rotational grassland, the potential surplus production was estimated by assuming that 5-20% of the total area of grassland can be allocated for bioenergy production. For permanent grassland the share allocated to energy production was assumed to be from 20-50%.

For estimating the potential of straw in the European Union, registrations of the cereal production from Eurostat was applied (Eurostat, 2015i). The straw potential was then estimated by assuming that the grain-to-straw ratio varies from 0.42 – 0.62, based on values from the literature (Höhn et al., 2014; Weiser et al., 2014; Edwards et al., 2006). The estimated straw yields were then reduced by respectively 10, 20 and 30% with the consideration that part of the straw could be applied for other purposes. Finally forecasts for the agricultural production of meat, milk and dairy in Europe and Central Asia (Bruinsma, 2012) were applied for estimating the production of animal manure, straw and grass in 2030.

The total energy potential for anaerobic digestion of the available manure from cattle, pigs and poultry in Europe in 2030 was estimated to be 20.83 Mtoe. Pig manure represents 9.66 Mtoe, cattle manure 9.22 Mtoe and poultry manure 1.92 Mtoe of the total potential.

The energy potential available from anaerobic digestion of grass from rotational grassland in Europe was estimated to range from 1.05 to 5.90 Mtoe. Depending on the availability the energy potential could be used to meet 8-44% of the total European production of biogas in 2013. The total energy yields from the potentially available grass yields from permanent grassland and meadows were estimated to range from 2.60 to 12.11 Mtoe. The results were seen to span a large range, depending on the assumptions for the availability of the grass. When assuming high availability of the grass, the estimated energy potential almost corresponds to the total European biogas production in 2013.

The total energy yields from the potentially available straw from cereal production in Europe were estimated to range from 14.76 to 28.02 Mtoe, depending on the availability of straw. Even when assuming a low availability of straw the potential energy yield is significant and could fully cover the total European biogas production registered in 2013.

In total the energy potential from the investigated resources ranges from 39.25-66.85 Mtoe, depending on the availability of the residues. In majority of the member states, straw and manure were estimated to represent the biggest energy potential. France and Germany were estimated to have the highest energy potentials, corresponding to 6.95-12.68 Mtoe and 6.38-9.71 Mtoe. In both countries the main sources for this potential are straw and manure. The UK was also estimated to have a significant energy potential (3.21-6.68Mtoe), mainly from straw but also from grass from permanent grassland and meadows. Grass from permanent grassland and meadows were also estimated to represent a significant energy potential if utilised in biogas production, ranging from 2.63 to 12.10 Mtoe. The possibilities of utilising grass from permanent grassland and meadows are of particular interest, as it does not require cultivation of the soil and potentially could prevent the loss of biodiversity on areas which are not being used today.

9 CONCLUSIONS, PERSPECTIVES AND FURTHER WORK

9.1. CONCLUSION

The objective in this dissertation was to identify and map biomass resources that have limited negative impact on nature, environment and climate and to assess the potential of utilising such resources in the current biogas sector.

In both Denmark and the European Union, biogas is expected to play an important role in reaching the energy policy targets as it is a storable and stable renewable energy source. The question of sustainability within the use of biomass resources are however under critical discussion as it is of crucial importance that the Earths ecosystems are handled and utilised carefully.

Four main categories of potentially sustainable biomass resources were identified: industrial residues, municipal residues, agricultural residues, and residues from landscape management. The research in this dissertation focused on the potential of animal manure, straw from cereal production, surplus forage grass from agricultural production, grass from nature conservation, and grass from roadside verges. These biomass types can be defined as agricultural residues and residues from landscape management.

The resource and energy potential from animal manure, straw, and surplus grass from both rotational and permanent grasslands and meadows were projected for year 2030 and mapped for the member states of the European Union. The energy potential from the investigated resources was projected to range from 39.3-66.9 Mtoe, depending on the availability of the residues. In majority of the member states, straw and manure were estimated to represent the biggest energy potential, but also the different types of grassland products holds a significant energy potential.

The potential of using excess grass from agricultural grass production as co-substrate in manure based biogas plants was estimated and mapped in the municipalities of the Region of Southern Denmark. An excess production of grass was estimated for several of the municipalities in the Region of Southern Denmark, but the excess production were found to be quite sensitive to the management practice of the grass fields and the productivity of the grass. The estimated yields were found to be sufficient to serve as sole co-substrate in 2-16 biogas plants with a capacity of digesting 200,000 t biomass annually. Optimised utilisation of grass not used as forage could thus contribute to an increased production of biogas in the region, without competing with food and feed production.

Roadside verges and meadow habitats in Denmark represent two currently unutilised sources for grass which can be used in the local biogas production. The potential and energy balance of utilising these resources were investigated and mapped in Denmark. The net energy yields from anaerobic digestion of the roadside grass in Denmark were estimated to range from 60,000 to 122,000 GJ, while 640,000 GJ for grass from meadow habitats. The energy return on energy investment when utilising roadside grass were estimated to range from 2.17 to 2.88. The net energy yield from anaerobic digestion of grass from meadow habitats in Denmark were estimated to represent 640.000 GJ and the energy gain on energy invested was found to range from 1.7 to 3.3. Despite the somewhat low values for the energy return on energy invested it was concluded that the use of roadside grass and meadow grass can contribute to a sustainable development of the Danish biogas sector. The concept of utilising grasses from nature habitats and roadside verges can function as a provider of renewable energy, a method for increasing the biodiversity of the nature habitats and roadside verges, and as a method for redistributing nutrients to the agricultural land.

The summarising conclusion drawn from this work is that a significant potential of the identified sustainable biomass resources are available in Denmark, but also on European level. In order to make these resources accessible for the bioenergy producers, the management practices of the resources must be changed in many cases. Such changes require investments, but they can also result in a range of significant positive externalities besides the production of renewable energy. The results show that a biomass resource base for a continuously progressive <u>and</u> sustainable development of the biogas sector is present in Denmark as well as the European Union.

Deteriorating and overuse of the ecosystems, as well as replacement of food and feed production does not have to be a precondition for bioenergy production. On the contrary, positive externalities from well managed bioenergy production systems can contribute in reducing environmental problems, and prevent the loss of biodiversity without conflicting the food and feed supply.

9.2. PERSPECTIVES

The results from this dissertation show, that biomass utilisation for bioenergy production can be done in sustainable manners. In particular the use of grass from nature conservation or roadside management can result in a range of positive externalities. The concept of combining of landscape management and bioenergy production holds several interesting possibilities. Depending on the ownership of the nature habitats, partnerships or corporation between the public authorities, private landowners, farmers, and the biogas sector can be stimulated and developed. Instead of considering energy production as the main purpose of biomass acquisition and utilisation, a more holistic approach including nature conservation, environmental protection, nutrient recycling and renewable energy production will be associated with the use of biomass. In the Region of Southern Denmark and Northern Germany where biogas production is strongly associated with large areas of intensively cultivated maize fields, such perspective could benefit the reputation of bioenergy sector. There is a need for innovative and interdisciplinary corporation across the different industrial sectors, authorities, and landowners, if sustainability is to be a part of bioenergy production. Recognizing the possibilities of bioenergy as a central part of the solution for several issues and not only a method for producing energy, is an important step towards sustainable bioenergy production.

Optimised use grass cultivated on agricultural land is another promising pathway for bioenergy production. The results in this study showed that there is a surplus production of forage grass in the Region of Southern Denmark, which could be used for biogas production. The highest potentials of surplus grass however required that the grass areas are cultivated intensively, which raises the risk of environmental degradation. As discussed in the study, recent research from Aarhus University however indicates that it is possible to intensify the cultivation of grass in order to obtain higher yields without casing environmental degradation. Separating the grass in a liquid protein rich fraction and a solid fibrous fraction makes it possible to use grass for more purposes than just ruminant fodder. The protein rich part can potentially be used as fodder for i.e. pigs and poultry, while the fibrous fraction can be used as fodder for ruminants, or utilised for bio-oil production via hydro thermal liquefaction (HTL) (Toor et al., 2011; Sørensen, 2014). In this context grass could become a central source of animal feed for the agricultural sector, replacing the import on soya proteins, or the area of fodder crops that requires more intensive cultivation practices than grass.

The potential of using sustainable biomass resources for biogas production combined with dynamic biogas utilisation is a possibility that can allow for a completely sustainable development of the regional biogas sector. As demonstrated by Jürgensen et al.,(2014), carbon dioxide from biogas and hydrogen deriving from electrolysis of surplus production of the fluctuating wind- and solar energy production in the region, can be used generate methane via the Sabatier process. Thus, biogas production can be part of solving the problems of storing the surplus energy, which cannot be used when the regional demand for electricity is low, via the European natural gas grid.

9.3. FURTHER WORK

Considering the results from this dissertation and the perspectives of sustainable bioenergy production, a range of further research areas of interest has emerged. The four research areas of main interest and relevance are presented below.

Due to the possibilities of utilizing grass for biogas production, mapping of the resource potential from other types of grass areas is found to be of relevance. Grass areas do not only represent a large share of the agricultural land, but is also found in residential and recreational areas. Although the potential of such areas can be expected to be less significant than the potential from agricultural areas, they still represent non-used resources which in many cases already are managed regularly thus the additional investments for acquiring the grass may be small.

Research and implementation of different partnership models, for example private-public partnerships, are of high relevance in order to motivate and facilitate the use of i.e. grass from nature habitats in biogas production. Knowledge sharing among the partners could inspire to new sustainable projects creating cross sectorial benefits.

Due to the possible positive externalities from the use of some biomass resources, it is of relevance to investigate the economic impacts of implementing such projects. The worth of benefits which cannot be directly measured in monetary terms, i.e. increased biodiversity and recreational value, can be of significance in political decision making processes. Thus such investigations could assist in initiating the use of sustainable biomasses, if financial support schemes for sustainable bioenergy production are introduced by the public authorities.

The possibility of integrating the use of sustainable biomass resources, dynamic biogas production, and production of high value products in biorefineries is another research topic of interest and relevance in the context of this thesis. Development and testing of dynamic and flexible systems could allow for a fully sustainable and efficient utilisation of biomass resources, wind- and solar energy. Implementation of such concepts represents promising perspectives in respect to changing the Danish and European energy supply to be based on 100% renewable energy sources.

LITERATURE LIST

© OpenStreetMap contributors. (2015). Denmark. Retrieved from http://download.geofabrik.de/europe.html

American Society of Agricultural Engineers. (2005). Manure production and characteristics. American Society of Agricultural Engineers, D384.2

Arodudu, O., Voinov, A., & van Duren, I. (2013). Assessing bioenergy potential in rural areas – A NEG-EROEI approach. Biomass & Bioenergy, 58, 350-350-364. doi:10.1016/j.biombioe.2013.07.020

Balstrøm, T., Jacobi, O., & Bodum, L. (2006). Bogen om GIS og getodata. (1st ed.). Denmark: Forlaget GIS og Geodata.

Bennett, E. M., Peterson, G. D., & Gordon, L. J. (2009). Understanding relationships among multiple ecosystem services. Ecology Letters, 12(12), 1394-1404. doi:10.1111/j.1461-0248.2009.01387.x

Boyle, W. C. (1977). Energy recovery from sanitary landfills - A review. In S. B. H.G. Schlegel (Ed.), Microbial energy conversion (pp. 119-138) Pergamon Press, Oxford, UK.

Bruinsma, J. (2012). European and central asian agriculture towards 2030 and 2050.FAO Regional Office for Europe and Central Asia.

Buttenschøn, R. M. (2007). Græsning og høslæt i naturplejen. Copenhagen, Denmark: Miljøministeriet, Skov- og Naturstyrelsen og Center for Skov, Landskab og Planlægning, Københavns Universitet.

Dahiya, A. (Ed.). (2014). Bioenergy. Biomass to biofuels (1st ed.). Saint Louis, MO, USA: Academic Press.

Daily, G. (1997). Nature's services: Societal dependence on natural ecosystems. Washington, D.C., USA: Island Press.

Delafield, M. (2006). A practical trial to investigate the feasibility of wide-scale collection of cuttings from roadside verges in Powys, for use in biogas and compost production. Welshpool, Wales: Montgomeryshire Wildlife Trust.

Durling, M., & Jacobsen, K. (2000). Slåtter av vägkanter med upptagaende slagslåtteraggregat - energianvändning och kostnader vid upptagning, transport och behandling. http://www.bt.slu.se/lt_old/Meddelande/Me2000-05/Meddel.pdf: Sveriges Lantbruksuniversitet - Institutionen for Lantbruksteknik.

Edwards, R. A., Šúri, M., Huld, T. A., & Dallemand, J. F. (2006). GIS-based assessment of cereal straw energy resource in the european union. Proceedings of the Expert Consultation “Cereals Straw Resources for Bioenergy in the European Union” 2006 Spain, Joint Research Centre of the European Commission IES JRC,CENER, National Renewable Energy Centre of Spain, , 17-21.

Ejrnæs, R., Wiberg-Larsen, P., Holm, T. E., Josefson, A. B., Strandberg, B., Nygaard, B., Andersen, L. W., Winding, A., Termansen, M., Hansen, M. D. D., Søndergaard, M., Hansen, A. S., Lundsteen, S., Baattrup-Pedersen, A., Kristensen, E. A., Krogh, P. H., Simonsen, V., Hasler, B., & Levin, G. (2011). In Asferg T., Ejrnæs R. and Hansen A. S. (Eds.), Danmarks biodiversitet 2010: Status, udvikling og trusler. Aarhus, Denmark: Danmarks Miljøundersøgelser, Aarhus Universitet.

Ellemann, L., Ejrnæs, , Reddersen, J., & Fredshavn, J. (2001). Det lysåbne landskab (Faglig rapport fra DMU nr. 372 ed.) Danmarks Miljøundersøgelser.

EurObserv’ER. (2014). Biogas barometer 2014. System Solaires le journal des energies renouvelables: EurObserv’ER.

European Commission. (2015). Press release- energy union: Secure, sustainable, competitive, affordable energy for every european. Retrieved from http://europa.eu/rapid/press-release_IP-15-4497_en.htm

Eurostat. (2015). Crops products - annual data [apro_cpp_crop] . Retrieved from http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=apro_cpp_crop&lang=en

Eurostat. (2015). Simplified energy balances - annual data [nrg_100a] . Retrieved from http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_100a&lang=en

Eurostat. (2015). Supply, transformation and consumption of renewable energies - annual data [nrg_107a] . Retrieved from http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do

Eurostat. (2015). Cattle population - annual data [apro_mt_lscatl]. Retrieved from http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=apro_mt_lscatl&lang=en

Eurostat. (2015). Cattle population- annual data - [apro_mt_lscatl]. .2015(March)

Eurostat. (2015). Pig population - annual data [apro_mt_lspig]. Retrieved from http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=apro_mt_lspig&lang=en

Eurostat. (2015). Population change - demographic balance and crude rates at regional level (NUTS 3). Retrieved from http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=demo_r_gind3&lang=en

Eurostat. (2015). Share of energy from renewable sources [nrg_ind_335a].

Eurostat. (2015). Slaughtering in slaughterhouses - monthly data [apro_mt_pwgtm].

Field, B. C. (2001). Natural resource economics - an introduction. New York, USA: McGraw-Hill/Irwin.

Field, B. C., & Field, M. K. (2006). Environmental economics an introduction. New York, USA: McGraw-Hill/Irvin.

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., & Zaks, D. P. (2011). Solutions for a cultivated planet Nature, 478(7369), 337-342. doi:10.1038/nature10452

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Gordon Bonan, Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N., & Snyder, P. K. (2005). Global consequences of land use. Science, 309(5734), 570-574. doi:10.1126/science.1111772

Garcia, R., & Millán, E. (1998). Assessment of cd, pb and zn contamination in roadside soils and grasses from Gipuzkoa (Spain). Chemosphere, 37(8), 1615-1625. doi:10.1016/S0045-6535(98)00152-0

Hald, A. B., Nielsen, L., Debosz, K., & Badsberg, J. H. (2003). Restoration of degraded low-lying grasslands: Indicators of the environmental potential of botanical nature quality. Ecological Engineering, 21(1), 1-20. doi:10.1016/S0925-8574(03)00023-5

Hall, C. A. S., Balogh, S., & Murphy, D. J. R. (2009). What is the minimum EROI that a sustainable society must have? Energies, 2(1), 25-47. doi:10.3390/en20100025

Herrmann, C., Prochnow, A., Heiermann, M., & Idler, C. (2014). Biomass from landscape management of grassland used for biogas production: Effects of harvest date and silage additives on feedstock quality and methane yield. Grass and Forage Science, 69(4), 549-566. doi:10.1111/gfs.12086

Ho, Y. B., & Tai, K. M. (1988). Elevated levels of lead and other metals in roadside soil and grass and their use to monitor aerial metal depositions in hong kong. Environmental Pollution, 49(1), 37-51. doi:10.1016/0269-7491(88)90012-7

Höhn, J., Höhn, E., Lehtonen, S., & Rasi, J. (2014). A geographical information system (GIS) based methodology for determination of potential biomasses and sites for biogas plants in southern finland. Applied Energy, 113, 1-1-10. doi:10.1016/j.apenergy.2013.07.005

Holm-Nielsen, J. B., Al Seadi, T., & Oleskowicz-Popiel, P. (2009). The future of anaerobic digestion and biogas utilization. Bioresource Technology, 100(22), 5478-5484. doi:10.1016/j.biortech.2008.12.046

Jørgensen, P. J. (2009). Biogas - green energy (2nd ed.). Aarhus, Denmark: Faculty of Agricultural Sciences, Aarhus University.

Jørgensen, P. J., Jørgensen, T. V., Nielsen, L., Pedersen, T., Bertelsen, I., Lærke, P. E., Hald, A. B., Høy, J. J., & Madsen, K. H. (2008). Biogasproduktion baseret på biomasse fra engarealer. nørreådalen – fase 1. BioM.

Jürgensen, L., Ehimen, E. A., Born, J., & Holm-Nielsen, J. B. (2014). Utilization of surplus electricity from wind power for dynamic biogas upgrading: Northern Germany case study. Biomass and Bioenergy, 66(0), 126-132. doi:10.1016/j.biombioe.2014.02.032

Kamm, B., & Kamm, M. (2007). Biorefineries –Multi product processes. Advances in Biochemical Engineering/Biotechnology, 105, 175-204. doi:10.1007/10_2006_040

Kern, M., Funda, F., Hofmann, H., & Siepnkothen, H. J. (2009). Biomassepotenzial von bio- und Grünabfällen sowie Landschaftspflegematerialien. Biomasse Forum, 107-190.

Lærke, P. E., Hald, A. B., & Nielsen, L. (2012). Næringstofbalans og miljö i enggræs. forsök med K-gödsling. In J. Lundegrén (Ed.), Evalueringsrapport marginale jorder och odlingssystem (pp. 35-42) BioM.

Levin, G., Jepsen, M. R., & Blemmer, M. (2012). Basemap: Technical documentation of a model for elaboration of a land-use and land-cover map for Denmark. (No. Technical Report from DCE – Danish Centre for Environment and Energy No. 11). http://www.dmu.dk/Pub/TR11.pdf: Aarhus University, DCE– Danish Centre for Environment and Energy.

Livestock Knowledge Transfer Management Team. (2001). Reducing silage loss. (No. ADAS/IGER 101). Bristiol, UK: University of Bristol.

Madsen, K. H., & Larsen, S. U. (2011). Vejen frem. Momentum, 3, 15-19.

Maestre, F. T., Quero, J. L., Gotelli, N. J., Escudero, A., Ochoa, V., Delgado-Baquerizo, M., García-Gómez, M., Bowker, M. A., Soliveres, S., Escolar, C., García-Palacios, P., Berdugo, M., Valencia, E., Gozalo, B., Gallardo, A., Aguilera, L., Arredondo, T., Blones, J., Boeken, B., Bran, D., Conceição, A. A., Cabrera, O., Chaieb, M., Derak, M., Eldridge, D. J., Espinosa, C. I., Florentino, A., Gaitán, J., Gatica, M. G., Ghiloufi, W., Gómez-González, S., Gutiérrez, J. R., Hernández, R. M., Huang, X., Huber-Sannwald, E., Jankju, M., Miriti, M., Monerris, J., Mau, R. L., Morici, E., Naseri, K., Ospina, A., Polo, V., Prina, A., Pucheta, E., Ramírez-Collantes, D. A., Romão, R., Tighe, M., Torres-Díaz, C., Val, J., . . . Zaady, E. (2012). Plant species richness and ecosystem multifunctionality in global drylands. Science, 335(6065), 214-218. doi:10.1126/science.1215442

Matson, P. A., Parton, W. J., Power, A. G., & Swift, M. J. (1997). Agricultural intensification and ecosystem properties. Science, 277(5325), 504-509. doi:10.1126/science.277.5325.504

McEniry, J., & O'Kiely, P. (2013). Anaerobic methane production from five common grassland species at sequential stages of maturity. Bioresource Technology, 127, 143-150. doi:10.1016/j.biortech.2012.09.084

McKendry, P. (2002). Energy production from biomass (part 1): Overview of biomass. Bioresource Technology, 83(1), 37-46. doi:10.1016/S0960-8524(01)00118-3

McKendry, P. (2002). Energy production from biomass (part 2): Conversion technologies. Bioresource Technology, 83(1), 47-54. doi:10.1016/S0960-8524(01)00119-5

Metzger, M. J., Bunce, R. G. H., Jongman, R. H. G., Mütcher, C. A., & Watkins, J. W. (2005). A climatic stratification of the environment of Europe. Global Ecology and Biogeography, 14(6), 549-563. doi:10.1111/j.1466-822X.2005.00190.x

Millennium Ecosystem Assessment. (2005). Ecosystems and human well-being: Synthesis. (). Washington, DC, USA: Island Press.

Møller, H., & Nielsen, L. (2008). Græs er ægte grøn energi - kan fordoble produktione af biogas. Forskning i Bioenergi, 23, 4-6.

Nielsen, K. A., Mikkelsen, M., Elbek-Pedersen, H., & Kristensen, H. (1991). Grovfoderproduktion. In Landsforsøgene (Ed.), Oversigt over landsforsøgene 1991 (pp. 249-294) Landskontoret for Planteavl.

Nielsen, L., & Hald, A. B. (2008). Management strategies to restore agriculturally affected meadows on peat-biomass and N, P-balances. Biodiversity and Animal Feed: Future Challenges for Grassland Production. Proceedings of the 22nd General Meeting of the European Grassland Federation, Uppsala, Sweden, 9-12 June 2008. Uppsala, Sweden. 153-155.

Nielsen, L., & Hald, A. B. (2010). Shortcut strategies to improve plant species richness after years of intensive management in moist grassland. Grassland in a Changing World. Proceedings of the 23rd General Meeting of the European Grassland Federation, Kiel, Germany, 29th August-2nd September 2010. Kiel, Germany. , 15 1052-1054.

Nielsen, L., Hald, A. B., & Larsen, S. U. (2012). Drift og pleje af enggræs. In J. Lundegrén (Ed.), Evalueringsrapport marginale jorder och odlingssystem (pp. 11-25) BioM.

Nielsen, L., Hald, A. B., & Badsberg, J. H. (2003). Slæt og afgræsning-betydning af tidspunkt og kombination for vegetation og produktion på engarealer. In A. B. Hald, C. C. Hoffmann & L. Nielsen (Eds.), DJF rapport - markbrug (pp. 59-84) Danmarks Jordbrugsforskning.

Nielsen, L., Hald, A. B., Debosz, K., & Badsberg, J. H. (2002). Genopretning af ferske enge-indikatorer for potentiel botanisk naturkvalitet. Forest & Landscape Research, 31, 100-131.

Noordijk, J., Delille, K., Schaffers, A. P., & Sýkora, K. V. (2009). Optimizing grassland management for flower-visiting insects in roadside verges. Biological Conservation, 142(10), 2097-2103. doi:10.1016/j.biocon.2009.04.009

Nygaard, B., Levin, G., Buttenschøn, R. M., & Ejrnæs, R. (2011). In Asferg T. (Ed.), Kortlægning af naturplejebehov: Notat vedr.delprojekt 1 i projektet: Sikring af plejekrævende lysåbne naturtyper i Danmark. Copenhagen, Denmark: University of Copenhagen.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., Church, J. A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N. K., Edenhofer, O., Elgizouli, I., Field, C. B., Forster, P., Friedlingstein, P., Fuglestvedt, J., Gomez-Echeverri, L., Hallegatte, S., Hegerl, G., Howden, M., Jiang, K., Jimenez Cisneroz, B., Kattsov, V., Lee, H., Mach, K. J., Marotzke, J., Mastrandrea, M. D., Meyer, L., Minx, J., Mulugetta, Y., O'Brien, K., Oppenheimer, M., Pereira, J. J., Pichs-

Madruga, R., Plattner, G. K., Pörtner, H. O., Power, S. B., Preston, B., Ravindranath, N. H., Reisinger, A., Riahi, K., Rusticucci, M., Scholes, R., Seyboth, K., Sokona, Y., Stavins, R., Stocker, T. F., Tschakert, P., van Vuuren, D., & van Ypserle, J. P. (2014). In Pachauri R. K., Meyer L. (Eds.), Climate change 2014: Synthesis report. contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. Geneva, Switzerland: IPCC Secretariat.

Parr, T. W., & Way, J. M. (1988). Management of roadside vegetation: The long-term effects of cutting. Journal of Applied Ecology, 25(3), 1073 -1087. doi:10.2307/2403767

Pick, D., Dieterich, M., & Heintschel, S. (2012). Biogas production potential from economically usable green waste. Sustainability, 4(4), 682-702. doi:10.3390/su4040682

Prochnow, A., Heiermann, M., Drenckhan, A., & Schelle, H. (2005). Seasonal pattern of biomethanisation of grass from landscape management. (No. 7). International Commission of Agricultural Engineering.

Qin, L. (2011). Can we get more out of our roads? The University of Twente.

Regionaldatenbank Deutschland. (2013). Bodenfläche nach art der tatsächlichen nutzung. Retrieved from https://www.destatis.de/DE/Publikationen/Thematisch/LandForstwirtschaft/Flaechennutzung/Bodenflaechennutzung.html

REN21. (2013). Renewables. global futures report 2013. Paris, France: Renewable Energy Policy Network for the 21st Century.

REN21. (2015). Renewables 2015 global status report. Paris, France: Renewable Energy Policy Network for the 21st Century.

Salter, A., Delafield, M., Heaven S, & Gunton, Z. (2007). Anaerobic digestion of verge cuttings for transport fuel. ICE-Waste and Resource Management, , 160(3) 105-112. doi:10.1680/warm.2007.160.3.105

Shafik, N. (1994). Economic development and environmental quality: An econometric analysis. Oxford Economic Papers, 46 (Special Issue on Environmental Economics), 757-773.

Smit, H. J., Metzger, M. J., & Ewert, F. (2008). Spatial distribution of grassland productivity and land use in Europe. Agricultural Systems, 98(3), 208-219. doi:10.1016/j.agsy.2008.07.004

Sørensen, K. L. (2014). Andre afgrøder kan fordoble produktionen. Effektivt Landbrug, 9.

Statbank Denmark. (2015). AFG07: Cultivated area by region, unit and crop. Retrieved from http://www.statistikbanken.dk/

Statbank Denmark. (2015). ANI7: Production and use of milk by unit. Retrieved from http://www.statistikbanken.dk/

Statbank Denmark. (2015). FODER1: Feed stuffs in agriculture by type of fodder, origin and unit. Retrieved from http://www.statistikbanken.dk/

Statbank Denmark. (2015). HST77: Harvest by region, crop and unit. Retrieved from http://www.statistikbanken.dk/

Staudinger, M. D., Grimm, N. B., Staudt, A., Carter, S. L., Chapin III, F. S., Kareiva, P., Ruckelshausm, M., & Stein, B. A. (2012). Impacts of climate change on biodiversity, ecosystems, and ecosystem services: Technical input to the 2013 national climate assessment: Technical input to the 2013 national climate assessment. Cooperative report to the 2013 national climate assessment. Washington, D.C., USA: United States Global Change Research Program.

Steffen, W., Richardson, K., Rockstrom, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De-Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. Science, 1-16. doi:10.1126/science.1259855

Stern, D. I., Common, M. S., & Barbier, E. B. (1996). Economic growth and environmental degradation: The environmental Kuznets curve and sustainable development. World Development, 24(7), 1151-1160. doi:10.1016/0305-750X(96)00032-0

Stern, N. (2008). The economics of climate change. The American Economic Review, 98(2), 1-37. doi:10.1257/aer.98.2.1

Swanson, S. E. (2001). GIS. Journal of Hospital Librarianship, 1(3), 83-89. doi:10.1300/J186v01n03_09

The Danish Energy Agency. (2012). Begrænsning for brug af majs og andre energiafgrøder til produktion af biogas. Copenhagen, Denmark: The Danish Energy Agency.

The Danish Energy Agency. (2014). Biogas i danmark –status, barrierer og perspektiver. Copenhagen, Denmark: The Danish Energy Agency.

The Danish Geodata Agency. (1976). DTK/4-cm kort (trykt 1957-1976). http://download.kortforsyningen.dk/content/dtk4-cm-kort-trykt-1957-1976: The Danish Geodata Agency.

The Danish Ministry of the Environment. (2013). Naturbeskyttelsesloven. Copenhagen, Denmark: The Danish Ministry of the Environment.

Tilman, D. (1999). Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices (papers from a national academy of sciences colloquium on plants and population: Is there time?). Proceedings of the National Academy of Sciences of the United States of America, 96(11), 5995-6000. doi:10.1073/pnas.96.11.5995

Toor, S. S., Rosendahl, L., & Rudolf, A. (2011). Hydrothermal liquefaction of biomass: A review of subcritical water technologies. Energy, 36(5), 2328-2342. doi:10.1016/j.energy.2011.03.013

Turkenburg, W. C., Beurskens, J., Faaij, A., Fraenkel, P., Fridleifsson, I., Lysen, E., Mills, D., Moreira, J. R., Nilsson, L. J., Schaap, A., Sinke, W. C., & Goldemberg, J. (2000). Renewable energy technologies. In J. Goldemberg (Ed.), World energy assessment: Energy and the challenge of sustainability (pp. 219-272) United Nations Development Programme.

Weiser, C., Weiser, V., Zeller, F., Reinicke, B., Wagner, S., Majer, A., & Vetter, D. (2014). Integrated assessment of sustainable cereal straw potential and different straw-based energy applications in germany. Applied Energy, 114, 749-749-762. doi:10.1016/j.apenergy.2013.07.016

Wise, S. (2014). GIS fundamentals (2nd ed.). Florida, USA.: Taylor Francis Group.

World Commission on Environment and Development. (1987). Our common future. New York: Oxford University Press