Nordic Energy Outlooks - Final report WP1

Bioenergy and links to agriculture & LULUCF in a Nordic context

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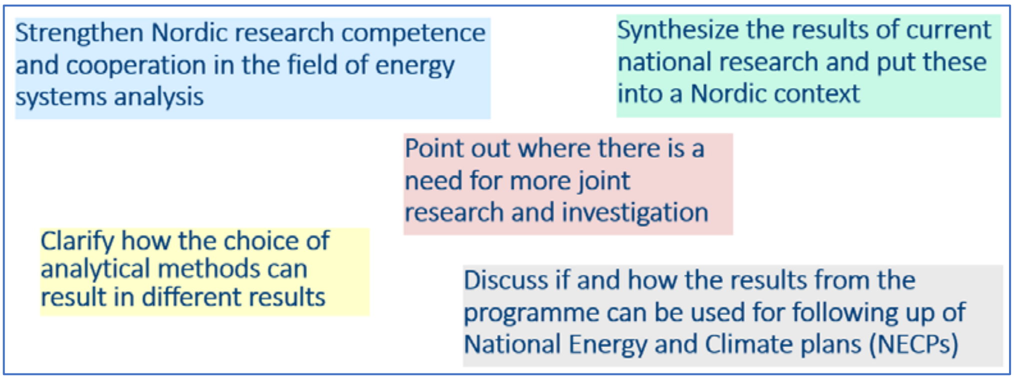
1. Introduction

1.1. About the Nordic Energy Outlooks programme

Nordic Energy Outlooks [1] (NEO) is a programme organised by Nordic Energy Research, and financed partly by Nordic Energy Research, the Swedish Energy Agency, the Research Council of Norway, and the Danish Energy Agency.

The main aim of the program is to *Strengthen Nordic research competence and cooperation in the field of energy systems analysis, by building on existing national research programs*. By creating a forum for collaboration between different research groups and institutions, NEO help to synthesize the results of current national research and put these into a Nordic context, but also help to clarify how the choice of analytical methods can create different results.

An additional aim of the programme is to discuss if and how the results from the programme can be used for following up on the integrated national energy and climate plans (NECP), and if the results can provide a regional perspective. Figure 1-1 illustrates the aims of the program.



Strengthen Nordic research competence and cooperation in the field of energy systems analysis

Synthesize the results of current national research and put these into a Nordic context

Point out where there is a need for more joint research and investigation

Clarify how the choice of analytical methods can result in different results

Discuss if and how the results from the programme can be used for following up of National Energy and Climate plans (NECPs)

Figure 1-1: Aims of the Nordic Energy Outlooks programme

The programme is divided into four work packages (WPs), as shown in Figure 1-2. Each WP is analysed by selected research environments in collaboration with Nordic Energy Research and SINTEF Energy – which is the project lead institution for the program.

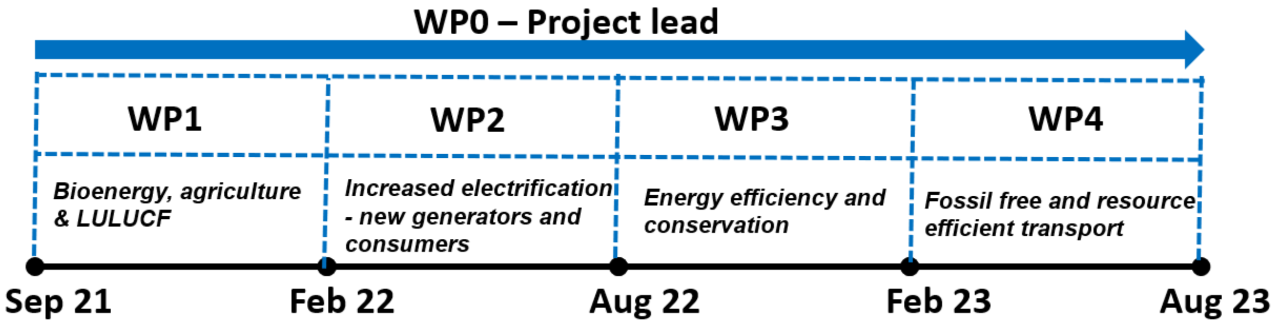


Figure 1-2: Overall timeline for Nordic Energy Outlooks

1.2. WP1: Bioenergy and links to agriculture & LULUCF in a Nordic context

This document is the final report from WP1, which addresses the role of bioenergy in the Nordic energy system and the corresponding implementation in energy system models.

The research partners in WP1 are SINTEF Energy/NIBIO, IVL, KTH, and DEA. Each research partner has committed to certain tasks in their own contract. The research questions pursued by each participant are described in **Section 1.1**. As described there, the work includes improvements in models and datasets, as well as review of literature to provide improved inputs to the models. Among the addressed topics are expansion of existing datasets to better represent the Nordic area, improvements of resource potentials and utilisation, LULUCF calculations (notably forestry), and emissions factor calculations.

The different models and corresponding datasets that have been developed through the project can be classified into:

- General energy system models (TIMES, GENeSYS-MOD)
- Domain-specific models for bioenergy (BeWhere, BioRes, and SiTree)

All relevant energy carriers, sectors, and technologies are in principle included in the general energy system models, whereas the domain specific models typically have a narrower focus allowing a more detailed representation, e.g. of biogas production, energy crops from agriculture, and forestry respectively. The different models are described in **Section 2**, both individually and in terms of how they relate to each other. An explicit comparative study of the numerical results from the different models is not included.

Section 3 describes the project outcomes from the research questions stated in **Section 1.1**. Improved models and datasets make it possible to provide more realistic views on the development of the Nordic energy system. In this way, the project has enabled involved research groups to produce more relevant knowledge for society in future projects.

Promising research topics for future cooperation are described in **Section 4**. As illustrated by Figure 1-3, ideas and thoughts have been developed in a process where all partners initially shared information, which then was studied and discussed between the partners in workshops. Through this process, the research partners have gained increased mutual understanding of the corresponding energy system models for the Nordic area.

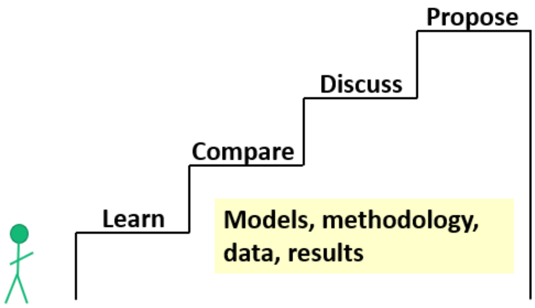


Figure 1-3: Process for mutual learning through WP1 activities

Section 5 discusses existing national energy and climate plans (NECPs) for Norway, Sweden, and Denmark. We consider if the results from the programme, and the expertise from involved researchers, can be used for following up NECPs by providing them with a Nordic perspective. **Section 6** concludes by providing a summary, and key takeaways from the work.

1.3. Research questions

Individual research questions for involved research institutes

Each involved research institute in WP1 had their own contract with their financing party, where corresponding research questions and goals were specified. This section describes the specified research questions for each institute. The corresponding outcome from the work is described in Section 3.

IVL

In Sweden, a large share of the energy supply comes from renewable sources such as hydropower, solar power, and bioenergy. As in the other Nordic countries, a substantial share is based on biomass. The biomass potential from forestry has been estimated several times. However, modelling the biomass potential from the agricultural sector, in terms of energy crops, straw, husk, grasses, and manure, is less investigated and not well integrated into energy system models. There are policy incentives to increase the domestic agricultural production in Sweden, contributing to larger yield and biomass waste streams. However, the transition to a bioeconomy also increases the demand for biomass in other sectors. This, in turn, contributes to intensified and competing land use, followed by adverse environmental effects such as declining biodiversity. According to different scenarios analysed in the AR5 report of the United Nations' Intergovernmental Panel on Climate Change [2], bioenergy will play an essential role in mitigating global warming in the coming decades. However, some aspects need further investigation so that the biomass potential in agriculture is used sustainably in the energy sector.

In this project, IVL developed and applied extensive knowledge regarding the TIMES (The Integrated MARKAL-EFOM System) model for the five Nordic countries and all energy conversion in all sectors, i.e. the Open Nordic TIMES (ON-TIMES) model. ON-TIMES is from the TIMES modelling family, a modelling concept and framework developed through more than 30 years in the IEA, TCP, ETSAP (International Energy Agency, Technology Collaboration Platform, Energy Technology System Analysis Program) [3]. ON-TIMES is an optimisation model that minimises total system cost given certain constraints, e.g. climate targets. The model structure is based on the TIMES-DK model [4], and developments in the Shift project [5] expanded to include the other Nordic countries in the NCES (Nordic Clean Energy Scenarios) [6] project. The ON-TIMES model was used to find the cheapest pathways to fulfilling each of the Nordic countries' climate targets, with a particular focus on sector coupling and potential synergies.

The overall aim of WP1 is to contribute to an increased knowledge and understanding of mechanisms that affect the biomass potential in the Nordic energy system, and investigate how the environmental impact of agriculture-based bioenergy can be assessed. This has been done by answering the following research questions:

- What is the estimated potential of agricultural biomass in the Nordics, and what are the main biomass sources from the agricultural sector?

- What are the key aspects affecting the biomass potential from agriculture in the Nordics, and how could the findings be integrated into the Open Nordic TIMES model (ON-TIMES)?
- What are the specifications of the energy system models and tools used in WP1? More specifically, what are in-data and outcomes, spatial and temporal resolution, etc.?
- How could ON TIMES be linked to the other tools and models used in WP1 to accurately represent the biomass use in agriculture and the rest of the energy system?

KTH

Sweden, Norway, and Finland are rich in biomass and have well-developed forestry industries. Denmark is dominated by agricultural land. There is enormous biomass potential in the Nordic Region, e.g. agroforest residues, and biogenic municipal waste. Biomass resources can be deployed to enhance energy security and use of renewables, and to address environmental (e.g. climate change, nutrient discharges) and socio-economic challenges (e.g. generating jobs). Out of the total biomass supply in the Nordic countries, forest biomass accounts for 70%, agriculture residues for 20%, and the rest is waste biomass. The key reason behind the upward trend is the increased use of biofuels in transport and of bioenergy for heating. It is estimated that bioenergy will be the single largest energy carrier in the Nordic region in 2050 [7], which raises the importance of sustainable biomass, especially with regards to impacts on land use change. Deployment of modern bioenergy is considered as a decarbonisation strategies [8].

In this WP, KTH investigated the role of modern bioenergy as a vector for low-carbon transformation in energy systems in the Nordic countries, with a focus on biogas production from agricultural residues and livestock manure. This work also explores how the sustainability aspects such as water use, emissions, fossil fuel and mineral consumption are accounted with the case of biogas production from the agricultural sector.

Methane, which is one of the main constituents of biogas, has received increased attention due to its potent global warming potential (GWP) and its enormous potential to be captured and utilised to replace fossil fuels.. Biogas is produced from the breakdown of organic matter in the absence of oxygen [9]. Nutrient/bio-fertiliser is also one of the co-products while making waste (residues and manure)-to-biogas. Biogas is a versatile energy carrier that can be derived from a wide range of organic substances [10]. Lönnqvist et al. [11] estimated the Swedish resource potential of biogas production from residues and energy crops. Forecasting the potential of Danish biogas production from livestock is done by Bojesen et al. [12]. Lately, the role of biogas and biogas-derived fuels in a 100% renewable energy system in Denmark is investigated using the EnergyPlan model by Korberg et al. [13]. Mapping of biogas production was done in 2010 in the Nordic Region [14]. However, the nexus with water-land-food-climate-energy systems for enhancing environmental benefits and resource efficiency has not yet been studied. Biogas production in a nexus approach has not been explored yet. There are limited studies that focus on analysing the impact of climate change in the agriculture sector.

The main objective of this study is thus to explore the biogas production from the agriculture sector (esp. agricultural residues and livestock manure) and identify the nexus with water-land-food-climate-energy systems. It is expected to generate new knowledge on the multiple benefits, e.g. energy and climate gains, agricultural productivity, bio-based economy in the Nordic Countries.

The *key research questions* are:

- What is the production potential of biogas from agriculture residues and livestock manure in the Nordic Countries?
- What are the sustainability aspects (emissions, water use, and fossil fuel/mineral consumption) in the production of biogas?
- How can biogas systems be integrated into the existing energy systems model and what will its role be in net-zero and/or 100% renewable energy (develop scenario for biogas in the region by 2050)?
- How can biogas from the agriculture sector be promoted in an integrated climate-land-energy-water nexus approach, while maintaining the ecosystems services?

When it comes to balancing the electricity grid, decarbonising the natural gas systems, and providing storage options, biogas plays a key role. Biogas serves as the versatile energy carrier for electricity production, use as a transport fuel or cooking gas. As such, the work is also linked with WP2 and WP3 in the Nordic Energy Outlooks programme. The work is also connected to WP4, as biomethane is considered the main alternative transport fuel.

SINTEF/NIBIO

The focus of this work is to investigate what can be gained by increasing the level of detail for the bioenergy sector in an overall energy system model. The current version of the open-source energy system model GENeSYS-MOD will be used as a reference. GENeSYS-MOD was developed in Germany with a Central European energy focus, without the high penetration of renewables and regional market and grid coupling that we see in the Nordic countries. Consequently, the assumptions and level of detail might not be optimal to represent the Nordic countries, and they can be improved by using results from sector specific models. GENeSYS-MOD includes biomass among the considered resources. Biomass in this respect is any kind of plant or animal material that can be used for energy purposes. In order not to compete with food production, only biogenic wastes and residues are included in GENeSYS-MOD, and the potential of non-waste biomass is not considered [15]. As the technical potentials of the different resources are key inputs to the model, the accurate estimation of the current and future potential of biomass is an important premise that will influence the model results. According to the report "Potential for bioenergy in the Nordics" [16], waste represents only 10% of the biomass supply potential of the Nordic countries. Therefore, a better estimate is needed to reflect the bioenergy potential more accurately in the Nordic countries.

As biomass use is predicted to grow markedly to reach the goal of decarbonising the energy sector, it is fundamental to understand the implications of such an increase. Land use, land-use change, and forestry (LULUCF) have a fundamental impact on the carbon balance in the atmosphere. An increased use of biomass for bioenergy may have an influence on LULUCF. Forest harvest residues (GROT) are tree components with a low market value, which are typically left on site after forestry operations and are very little used today. Increased use of GROT was highlighted as a relevant measure in a Norwegian climate report (Klimameldingen) [17], which led to a subsidy scheme for removal of GROT for bioenergy (the scheme was introduced in 2009 but discontinued in 2014). Therefore, harvest residues could play a role in the bioenergy sector both in the short and long term.

Under these premises, within this project, we want to answer the following main research questions:

- How can we take advantage of the results from sector models specific for the bioenergy sector, such as results from resource potential calculations to improve the quality of the analysis of a complete energy system?
- How do different assumptions on bioenergy in an energy system model (e.g. current and future bioenergy potential) affect the results of the analysis?
- How will the evolution of bioenergy influence the LULUCF sectors and how can sector specific models be used to interpret and extrapolate the results of global energy system analysis on future scenarios for bioenergy utilisation?

Danish Energy Agency (DEA)

The participation of the Danish Energy Agency (DEA) focuses on taking part in, learning from and contributing to the modelling and understanding of the linkages between AFOLU (Agriculture, Forestry, and Land Use) and the energy systems – specifically bioenergy. Denmark is currently developing strategies to reach the climate goal defined in the Climate law of 6 December 2019 [18]. Reaching the defined goal of a 70% reduction of GHG emissions in 2030 (compared to 1990 levels) and climate neutrality by 2050 requires an integrated approach combining emissions reductions with CO2 sequestration. The DEA has an active modelling community contributing to the development of the Danish governmental climate plans within the areas of energy, agriculture and LULUCF. For several years, energy system modelling has been a part of the DEA energy prognoses and there is extensive knowledge on the applicability and functionality of the different models.

The DEA is responsible for the annual publication of the national Greenhouse gas status and projection report (*Klimastatus og – fremskrivning*) and collaborates closely with Aarhus University, especially regarding the Danish agricultural and LULUCF sectors. For this reason, substantial efforts are directed towards model development of GHG emissions from agriculture and LULUCF while seeking integration with other sectors, especially energy and waste. Accurate representation of biomass flows and potentials are important to evaluate how to best allocate and utilise biomass across energy, agriculture and LULUCF sectors and end-uses. The DEA recently commissioned the BioRES model. This model, developed by Energy Modelling Lab, is to our knowledge the first attempt at modelling biomass resource flows across all relevant sectors in a Danish setting, and as such the hope is that the BioRES model can provide useful input for other energy system models (both in Denmark and in a Nordic context) in terms of the potential of biomass in different scenarios.

Within WP1 of this NEO project, the DEA participates in-kind with modelling expertise, experience sharing and knowledge exchange, specifically related to TIMES, energy systems, greenhouse gas emissions from agriculture, and LULUCF by. The research goals were formulated as follows:

- Participate in dialogues across the Nordic region on issues related to modelling energy systems and linkages to agriculture and LULUCF.
- Learn from the experience of Nordic research institutions regarding modelling bioenergy systems that link to agriculture and LULUCF while exploring the improvement potential for data gaps. Specifically provide data of biogas production plants in Denmark for utilisation in the BeWhere model.

- Contribute to Nordic Energy Research by sharing insights from Danish modelling of bioenergy systems with linkages to agriculture and LULUCF by: a) Describing IntERACT (TIMES-DK), focussing on where the model could receive data from the agriculture and LULUCF sectors, and b) Describing and illustrating the modelling approach of BioRES with respect to tracking biomass resource flows and estimating greenhouse gas emissions.

In summary, the overall research goal set by the DEA relates to improved understanding of modelling concepts (models, datasets etc.) utilised in the Nordic region for modelling bioenergy by linking energy and models to couple the energy sector with agriculture and LULUCF more explicitly.

2. Description of models

2.1. The need for further development of energy system models

All involved research institutes apply and develop energy system models, which include bioenergy products, for the whole Nordic area or a part of it. There is always a need for further development of such models for many reasons, including technological development, new policies at the national or EU level, new products or markets, improvements in modelling techniques or computers, or available inputs. The current section describes the corresponding models developed during the project, i.e. prior to the development carried out within the project. The improvements to the models – and other project outcomes – are then described in Section 3.

The general energy system models that in principle include all energy carriers and all sectors are described in Section 2.2, whereas the domain-specific models for bioenergy are described in Section 2.3.

2.2. Energy system models

ON-TIMES

The TIMES energy system model is used to optimise energy systems over a mid-to-long-term horizon. The model is driven by exogenously given demands for energy services and is based on a perfect-foresight or rolling limited foresight, linear programming bottom-up approach, where the objective function is the minimisation of the total system cost. TIMES model represents energy systems by different processes connected by 'commodities' flows. Each process (i.e., energy conversion technology) is described, for example, by its input and output commodities, efficiency, availability, lifetime, and costs, whereas each commodity (e.g., fuel) is described, for example, by its availability, extraction or import cost and environmental impacts.

The ON-TIMES model used in this study includes the five Nordic countries in more detail (Denmark two regions, Sweden four regions, Norway two regions, Finland two regions, Iceland one region) and the surrounding countries represented by trade-links and price profiles for traded commodities. Energy sectors represented in the model are upstream/ fuel production, power and heat, heavy industry, residential, transport and other sectors (i.e., manufacturing industries, services and agriculture). The model has a time horizon between 2015 -2050, in 5-year time steps. Each model year is divided into 32-time slices. ON-TIMES can be soft linked to a BALMOREL model, which analyses dispatch and operation focusing on the electricity system. The BALMOREL model covers power systems in 18 European countries, including Denmark, Finland, Norway and Sweden [19]. The current version of the BALMOREL model contains three main scenarios which were designed to meet the carbon neutrality target by balancing carbon emissions in the Nordic countries.

The main model inputs to ON-TIMES are techno-economic data of existing energy conversion technologies, current and future resource and LULUCF potential, fuels prices and (if relevant) the associated CO_2 emissions, demands projections for different energy services, techno-economic data of new conversion technologies, which are used as investment options and model constraints, e.g., CO_2 emissions cap. The entire ON-TIMES energy system model is available on GitHub – Nordic Energy

Research NCES [20]. It contains all sector-level technology data and all demand projections with the associated references.

The current version of the model contains three main scenarios which were designed to meet the carbon neutrality target by balancing carbon emissions and sinks in the Nordic countries as below:

- Carbon Neutral Nordic (CNN) seeks the least-cost pathway, considering current national plans, strategies, and targets.
- Nordic Powerhouse (NPH) explores the opportunity for the Nordics to play a more prominent role in the broader European energy transition by providing clean electricity, clean fuels, and carbon storage.
- Climate Neutral Behaviour (CNB) reflects Nordic societies adopting additional energy and material efficiency measures in all sectors, ultimately leading to lower demand for both.

For each scenario and model year, the primary model outputs are installed capacities of energy conversion technologies, fuel use, production per conversion technologies and marginal energy and CO_2 prices. The model also generates results for primary energy supply by energy source, CO_2 emissions, investment capacities, carbon capture level, final energy consumption by energy source, final energy consumption by sector.

In the ON-TIMES model, the agricultural sector is represented with several conversion technologies that currently fulfil the sector's heat demand. There are different types of heat pumps, centralized and decentralized district heating, and heat-only boilers in detail. Fuel input to the heat-only boilers includes natural gas, coal, diesel, biogas, heavy oil, LPG, waste, and electricity. In addition, current diesel-fuelled tractors, trucks, fishing boats, forestry machines, LPG-fuelled forklifts, electric light appliances and motors are also considered. The existing technologies are gradually replaced with new technologies (due to either reaching their lifetime or constraints on CO_2 emissions) given as new investment options in the model. These are woodchips boilers, heat pumps with waste heat recovery, electric boilers, mechanical vapor recompression, booster heat pumps, infrared heating, oil, gas and coal boilers, solar, centralised, and decentralised district heating.

In the model, the biomass sources from agriculture, including straw, grass, corn, rapeseed, sugar beet, deep litter, manure (gylle) and the corresponding potentials for 2015, 2030 and 2050 are represented in detail (see Table 2-1)

In the model, fossil and renewable (e.g. biomass) fuels, excess heat, renewables (hydro, solar, geothermal, wind) in all the energy sectors are represented as energy carriers. The model covers 81% of total GHG emissions (excl. LULUCF) in the Nordic countries in 2017, in which CO_2 emissions associated with fossil fuel use in refineries, power and heat, domestic transport, international transportation, buildings, and industry have been considered. The emissions from LULUCF for different types of land use in the Nordic countries have not been modelled, but these are exogenously included in the model in an aggregated way. Since emissions from LULUCF is included in the model, biomass use in the energy system is not associated with any environmental impact to avoid double counting.

Table 2-1: Agricultural biomass and the corresponding potentials in ON-TIMES (PJ) *)

	Sweden	Denmark	Norway
Straw	67.6/ 37/ 37	44/ 66/ 66	8/ 8/ 8
Grass	11.4/ 11.4/ 11.4	5/ 5/ 5	0/ 0/ 0
Corn	0.4/ 7.3/ 7.3	2.7/ 15.3/ 15.3	2.7/ 15.3/ 15.3
Rapeseed	0.4/ 7.3/ 7.3	2.7/ 15.3/ 15.3	2.7/ 15.3/ 15.3
Sugar beet	0.4/ 7.3/ 7.3	2.7/ 15.3/ 15.3	4.1/ 4.1/ 4.1
Manure	15/ 15/ 15	31/ 40/ 40	27/ 27/ 27

*) The values are given for 2015/ 2030/ 2050. In the model these potentials are allocated to each region of the corresponding country based on the region's land area.

IntERACT (TIMES-DK)

The IntERACT model is a Danish hybrid model, which integrates a general equilibrium framework into a TIMES energy system model [21]. IntERACT shares many similarities with ON-TIMES. I.e., the energy system part of IntERACT is solved using a linear programming bottom-up approach, where the objective function is to minimise the total discounted system cost over the selected optimisation period. However, IntERACT also facilitates a mode where demand for energy services becomes endogenous by relying on an iterative link to a general equilibrium submodel. In this setting, energy service demand from various sectors results from the cost of services and economic growth assumptions [22].

Within the Danish Energy Agency IntERACT is used for three overall purposes:

1. To determine industry and household emissions and energy use within policy scenarios (Danish Energy Outlook).
2. To assess the impact of different policy measures directed at households and industry.
3. For explorative scenarios dealing with how meeting Danish long-term climate policy goals may look when considering different pathways.

When using IntERACT for explorative scenarios, emissions from AFOLU (Agriculture, Forestry, and Land Use) follows exogenous projections. This ensures that IntERACT represents all relevant GHG emissions, although only emissions related to the energy system are endogenous within the model.

GENeSYS-MOD

The Global Energy System Model (GENeSYS-MOD) is an open-source global energy system model that focuses on coupling between the different energy sectors, i.e. transportation, electricity, and heat [23]. Through an optimisation procedure to minimise costs, the model elaborates scenario pathways for how the energy system could evolve to meet predefined demand and emission targets. Results from the model for four fully open European decarbonisation scenarios are openly available through the open Platform of the H2020 EU project openENTRANCE [24]. The project investigates different pathways for the transition to a reduced-emission and low-carbon future. The scenarios and simulation results and analyses can provide important information for companies and decision makers and help them make more informed choices and investments on the way to reaching a climate neutral Europe in 2050.

GENeSYS-MOD is based on the Open-Source Energy Modelling System (OSeMOSYS [25]) framework. While still part of the OSeMOSYS family of models, various aspects have been redesigned, expanded, or added in GENeSYS-MOD. The current model is a linear program, that minimises total system costs. Energy demands in different forms (i.e. transport, electricity, and heat) for the different sectors (i.e. industry, residential, other sectors) are exogenously predefined over the modelled timeframe, e.g. five-year timesteps from today to 2050 for scenarios developed in openENTRANCE. How the current energy system looks like is also a predefined input to the model, together with resource potentials, emission intensities and costs associated with the different fuels and technologies. GENeSYS-MOD seeks to find the most cost-effective way to satisfy the changing energy demand over the years, with one of the main constraints to the optimisation being a limit on emissions over the considered period.

A specific strength of the model framework is its flexibility when it comes to spatial resolution. Based on the specific focus and the available input data, calculations can be customised to be from a neighbourhood or regional level to a global scale. In the present work, the spatial resolution considers Norway detailed into 5 nodes, 1 node in Sweden, 1 node in Denmark, 1 node in Finland and 1 node for the rest of Europe. Also, the time resolution is flexible, and for the current analysis a temporal resolution of every 488th hour for the results has been chosen due to extensive computation time. Calculations are typically performed with 2050 as a time horizon and with 5-year timesteps.

In Open ENTRANCE, GENeSYS-MOD has been linked to a variety of both open source and proprietary models, among others powers system, local energy system and transmission expansion models such as REMES [26], EMPIRE [27], EMPS [28], openTEPES [29], GUSTO [30], and EXIOMOD [31].

The openly available European data set is developed within the openENTRANCE project. This is a comprehensive dataset for Europe, containing 29 European countries and a non-EU Balkan region, with and mostly based on Eurostat, national statistics, and academic literature. The current version of the dataset contains 4 different scenarios [32] through which Europe can reach a decarbonised energy system [33] in 2050:

- Techno-Friendly (1.5°C): Based on a general positive societal attitude towards the adoption of new technologies and rapid technical development.
- Directed Transition: Based on strong policy incentives to lead the adoption of low-carbon and carbon-mitigating technologies and rapid technological developments.
- Societal Commitment (1.5°C): Based on the assumption of a strong societal commitment to transitioning to a low carbon economy and government action. No major technological breakthroughs are considered.
- Gradual Development (2°C): Based on a little of each of the above scenarios (i.e. technological effort, policy effort and societal effort).

The GHG emission budgets for Europe needed for the 1.5°C and 2°C goals are results obtained from MESSAGE-Globium [34]. An important assumption in the scenarios is an overall reduction in primary energy demand due to a general increase in efficiency promoted by different factors, especially electrification.

First results from the scenario runs highlight the need for further country specific constraints that mirror important political decisions and plans. One interesting observation in the Norwegian results is that oil and gas production stop consequently across all scenarios, early in the modelling timeframe, in some cases as early as 2025. This is not likely to happen. Moreover, the model's choice to build large amounts of onshore wind in Norway might be politically not viable. These examples showcase the discrepancy between a systemwide optimal and lowest cost solution to a decarbonised system versus political reality.

GENeSYS-MOD does not have a specific focus on bioenergy, but biomass is one of the resources available for energy production. The biomass-based resources considered by the model are grass, wood, residues, paper & cardboard and roundwood.

2.3. Sector-specific models

BeWhere

There is a plethora of bioenergy systems models. Under the bioenergy umbrella, BeWhere [35] is developed to optimise the supply chains of modern bioenergy production considering the total systems costs, lifecycle emissions, and associated environmental burdens [36]. The model is used to investigate optimal localisation of biofuel production on a European scale [37], optimal locations of advanced biofuels refineries in Sweden [38], and Finland [38]. Khatiwada et al [39] and Harahap et al [40] have also used the model to find the optimal configurations of agro-based biofuel refineries in Brazil and Indonesia respectively.

Spatially explicit BeWhere model is applied to optimise the utilisation of livestock manure and agricultural residues for biogas production in the Nordic region. BeWhere is a techno-economic engineering model for renewable energy systems optimisation, which identifies the location, size and technology of renewable energy systems applied to specific regions, assessing capacity factors, energy storage, and other economies of scale. BeWhere can estimate the economic benefits and consider environmental parameters (including supply chain emissions and reductions) of substituting renewable energy for fossil-fuel-based production. Figure 2-1(a) illustrates the biogas supply chains in the BeWhere model configuration.

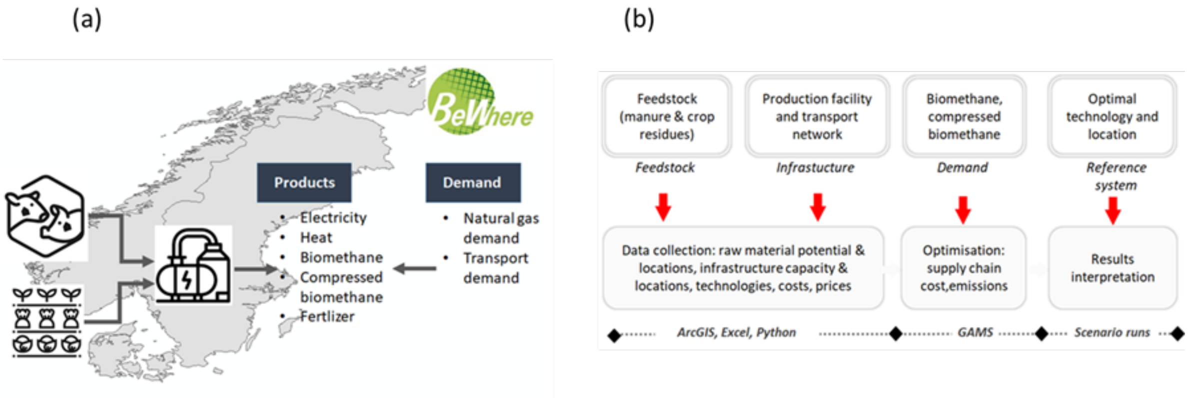


Figure 2-1: (a) Illustration of biogas supply chain for BeWhere model configuration and (b) modelling procedure in this study

The BeWhere model optimises renewable energy systems through cost minimisation for the welfare of the region. The model incorporates the techno-economic, spatial, and temporal components to optimise location, capacity, technology and timing of energy conversion sites. The model identifies the most-cost effective technology at each plant and total bio-products generated. It will determine the supply location to provide feedstock for the biogas system.

BeWhere is developed in the commercial software GAMS, uses a CPLEX solver, and the studied problem is expressed via Mixed Integer Linear Programming (MILP). MILP is the most common approach for designing biomass-to-bioenergy supply chains [41]. The model is schematically represented with nodes and arcs – a network that consists of nodes and connection between them. Each arc associates to a continuous variable. MILP allows the modelling of discrete (binary) variables. In this study, the binary variables are associated to the plant nodes to select the lowest cost technology for biogas/biomethane production – i.e. location for modern bioenergy plants. The model chooses the optimal pathways from one set of biomass supply points to a specific plant and, further, to a set of demand points. Modelling procedure and components is presented in Figure 2-1(b).

The BeWhere modelling framework proposed for this study also follows the MILP principle but includes the spatial and temporal assessment. The Nordic countries are aggregated according to 30 x 30 km. The temporal (multi-period) assessment is performed between 2020 to 2050, with 5 years' time step. The different components, shown in Figure 2-2, along the chain are raw materials, processing plant, intermediate products, conversion technologies, bio-products, and demand for the final products.

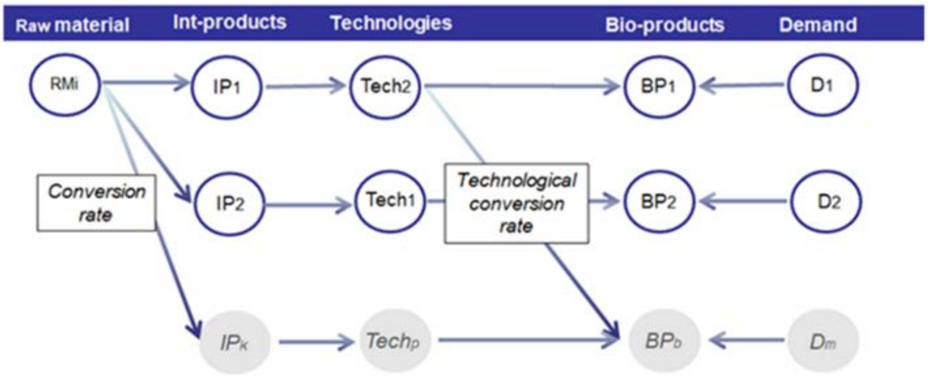


Figure 2-2: BeWhere model structure and components for biogas supply chain

This project defines the objective function to minimise the total cost along the product(s) supply chain. This is formulated as follows:

*Minimise (net total supply chain cost + carbon tax * total supply chain emissions)*

The supply chain cost consists of feedstock production, feedstock transport to operating plant and technology cost. The supply chain emissions include emissions from process inputs, feedstock production, transport, and plant operations. Avoided emissions, for example bio-digestate production replaces fossil-based fertiliser and avoiding methane emissions, is subtracted from the total supply chain emissions. Avoided costs, for example potential revenue gained from the sale of by-product (i.e. bio-digestate) contributes to the reduction of plant operational cost. The cost of GHG emissions is internalised in the model in the form of a CO_2eq tax. The model solves the problem by selecting the least costly technological option, considering the whole supply chain cost, emissions, and prices. Environmental burdens such as water loss and biodiversity loss can also be monetised considering the external damage costs. Thus, the model does not optimise the profit of a single plant but rather consider the entire systems for the welfare of the region.

The main BeWhere input data is presented in Table 2-2. Some simplifications might be considered to accommodate data availability.

Table 2-2: BeWhere main input data

Biomass supply/availability • Sustainable supply of biomass • Quality and quality of feedstock • Production scenarios	Distribution and infrastructure • Road, train network • Power lines • Power stations and energy grid
Production costs (techno-economic parameters) • Transport and distribution costs • Conversion efficiencies • Plant setup and operation & maintenance	Demand projection/sites and targets • Plans for expansion of infrastructure • Demand of energy • Goals, targets, and policy scenarios
Cost and price structure • Power/heat price • Fossil fuel use • Prices/costs of feedstock and renewables	Environment • Emissions (climate change) • Water loss • Biodiversity hotspots

The material balance of input and output in this study is subject to a few constraints and assumptions, described as follows:

- The amount of feedstock (livestock manure and agricultural residues) that can be utilised for biogas production cannot exceed the feedstock availability.
- The maximum feedstock transport distance is limited.
- The material balance from feedstock to intermediate products then final products are applied based on the plant capacity and technological conversion rate.
- The binary variable is used to restrict the selection of biogas conversion technology (whether to build or not) and the plant capacity that is suitable to convert the intermediate product to final product.
- In the inclusion of the temporal dimension, a technology with a specific size and location that is selected in year (*y)* remain until the end of the assessment period.
- The system is constrained by the biogas demand in Nordic region.

BioRES

Accurate representation of biomass flows and potentials are important to evaluate how to best allocate and utilise biomass across energy, agriculture and LULUCF sectors and end-uses. The BioRES model, developed by Energy Modelling Lab [42], is an easy-to-use excel based tool for exploring biomass flows across different sectors towards 2030 and 2050 within a Danish context. The model relies on wide set of exogenous input, including land use, wetland restoration on cultivated organic soil, afforestation, biogas-production, future animal production, future dietary behaviour of the general population etc.

The design of the BioRES model makes it ideal for making explorative bioenergy scenarios. Scenarios which can then be used to facilitate dialog between different stakeholders or serve as input to dedicated energy system models, such as ON-TIMES, IntERACT, and GENeSYS-MOD.

The BioRES model further includes a submodule that provides an around-about estimate of GHG emissions. Greenhouse gas emission estimates in BioRES are based on the national GHG inventory submitted in 2020 for the year 2018. Estimating GHG emissions from agriculture and LULUCF is methodologically complicated and requires detailed activity data if done according to the methods defined by the IPCC in the guidelines for GHG inventory reporting. The around-about estimates of GHG emissions from BioRES reflect implied emission-factors derived per unit of a specific activity, e.g., number of animals or crop type, which is not necessarily in accordance with IPPC guidance. These emissions factors do not consider structural changes, mitigation measures, or even the impact of climate change. Calculated GHG-emission from the BioRES model, hence, cannot stand alone and will for some sources deviate substantially from emissions projections made using IPCC-defined methods for national GHG emissions.

SiTree

The SiTree package provides a framework to build an open-source single-tree simulator, being a flexible tool that may operate at the individual-tree level and accommodate also other ecosystem services such as carbon sequestration [43]. SiTree is written in the R language for statistical computing [44]. SiTree is designed to run single tree simulations where trees can be defined by two time-dependent variables (such as diameter (or basal area), and height), and on time-independent variable, such as tree species. It keeps tracks of all alive, dead, and removed trees in a robust, fast and memory efficient way. Two types of input are required by SiTree: tree level (including stand/plot ID, tree ID, diameter, height, and tree species) and stand level (including plot ID, plot size, elevation, site index, plot coordinates, distance to road, temperature, or precipitation). SiTree simulates future growth, mortality, ingrowth, and natural regeneration of trees as well as management, if any. Increment, mortality, and ingrowth of individual trees are forecasted either by a traditional empirical model-based approach or by imputation. Functions can also be defined that affect characteristics of the stand (external modifiers), such as climate change, or fertilisation. The simulator includes single-tree models for Norway and uses the soil model Yasso07, such that also changes in the soil organic carbon (dead wood, litter and soil pools) from forest land on mineral soil may be forecasted [45]. SiTree can flexibly accommodate a set of different silvicultural management options, different harvest pathways [46], and changes in forest productivity due to changing climatic conditions [47]. Recently, the SiTree simulator has proven to be a valuable tool to analyse the effect of different climate mitigation measures in Norwegian forest [48-50], and in establishing a forest harvest reference level for Norway [51].

The SiTree framework has previously been used to project the future growth, mortality, ingrowth, and natural regeneration. Nearest neighbour (nn) imputation algorithms are methods to estimate one or several variables for each tree or plot using values obtained from related cases in the reference database. The reference database is compiled using remeasurements from the Norwegian Forest Inventory (NFI) in the 2003-2017 period. For example, to estimate growth, and mortality of a tree (target tree) during the simulation, we look for a similar tree in similar conditions (e.g., competition and social status) in the reference database, once we found the most similar tree in the reference database (reference tree), we assign its growth and life/death status to the target tree. In a similar way ingrowth can be imputed at plot level. To estimate ingrowth for a target plot one finds a similar plot in the reference database with similar characteristics (e.g., site index, basal area, and species composition), and assigns the ingrowth of the reference plot to the target plot, that is, the same number of trees, of the same size and species are assigned to the target plot. Volume and biomass are estimated using single-tree allometric functions as described in Breidenbach et al. (2020) [43]. Simulations were carried out in 5-year time intervals for the period 2018 - 2102. All simulations were carried out on the Norwegian NFI network of permanent sample plots [43]. The Norwegian NFI consists of 250 m2 permanent circular plots systematically distributed and stratified across the country, where 1/5 of these plots are inventoried annually in an interpenetrating panel design on a 5-year cycle. The NFI stratification is based on forest productivity, resulting in a grid spacing of 3 km × 3 km, 3 km × 9 km, and 9 km × 9 km for lowlands and productive regions in northern Norway (Finnmark county), low-productive alpine regions not located in Finnmark, and Finnmark alpine regions, respectively. Within each plot, tree species, tree status (alive or dead), and diameter at breast height (DBH) are recorded for all trees with a DBH ≥ 5 cm. Additionally, tree height is measured for a subsample of 10 trees per plot based on a basal area factor and predicted for those trees without height record.

In order to provide the most updated and useful data about the harvest residue availability from the forest sector in Norway, we identified a business-as-usual scenario (BAU) reference scenario, based on five forest management established practices and measures. Specifically, we considered current practices regarding regeneration after felling, planting density, genetic improvement, fertilisation, and pre-commercial thinning. All measurements considered comply with regulations regarding forest management in Norway [52], including environmental requirements and considerations. Harvest volumes were predicted based on SiTree and followed a similar approach to Søgaard et al., 2019 [53] Figure 2-3. Plots were ranked according to the probability of harvest and harvest started at the ones with higher harvest probability until the target harvest intensity was reached. Simulations did not include land use changes over time, so the forest area was considered constant from 2017. Simulations were carried out under assumptions of future climate changes corresponding to the representative concentration pathway (RCP) 4.5.

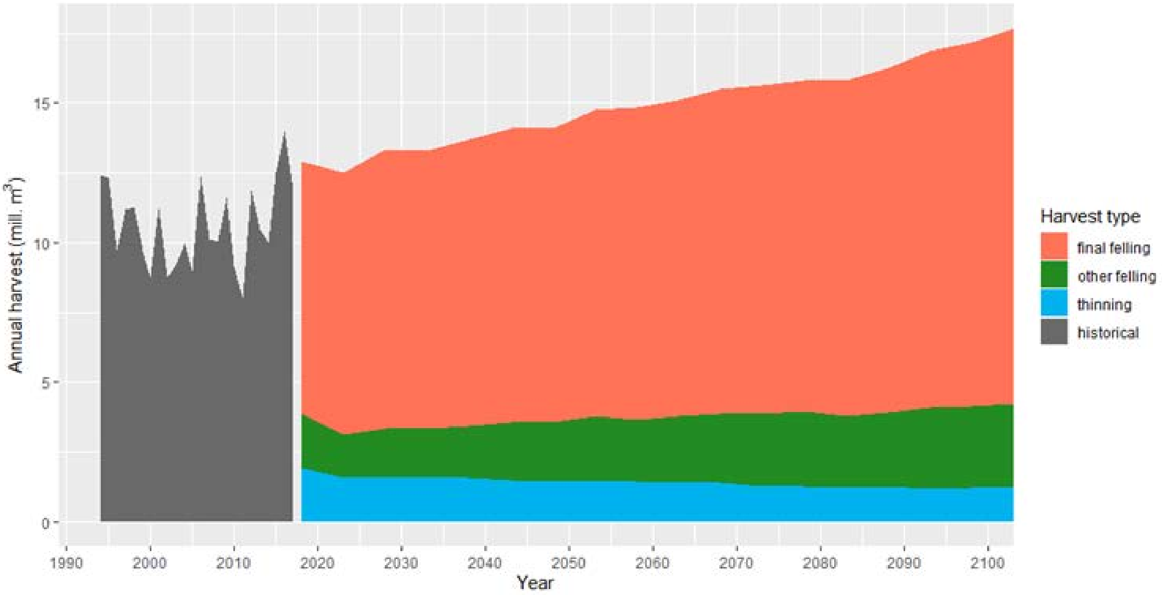


Figure 2-3: Project development in harvest rates

2.4. Relations and differences between models

Figure 2-4 and Figure 2-5 illustrates some of the properties of the considered models. Figure 4 illustrates the geographical coverage and shows if it is an optimisation tool or a simulation tool. Figure 2-5 illustrates the geographical coverage of the models, and which energy products are included. Note that the illustrations are simplification compared to the degree of detail in several models.

As shown in Figure 2-4 and Figure 2-5, all the optimisation tools are programmed in GAMS, whereas different programming languages are applied for the simulation tools. ON-TIIMES and GeneSys-Mod, which both are general energy system models, includes the whole Nordic region and more. The domain-specific model BeWhere, which focuses on biogas, is also developed to cover the whole Nordic area. The other models are currently for one country. For Denmark, IntERACT (TIMES-DK) is a general energy system model, whereas BioRES focuses on the link between agricultural outputs and the corresponding energy bi-products. For Norway, SiTree is a framework to implement an individual tree simulator. In this context, residue available for energy purposes is an important output.

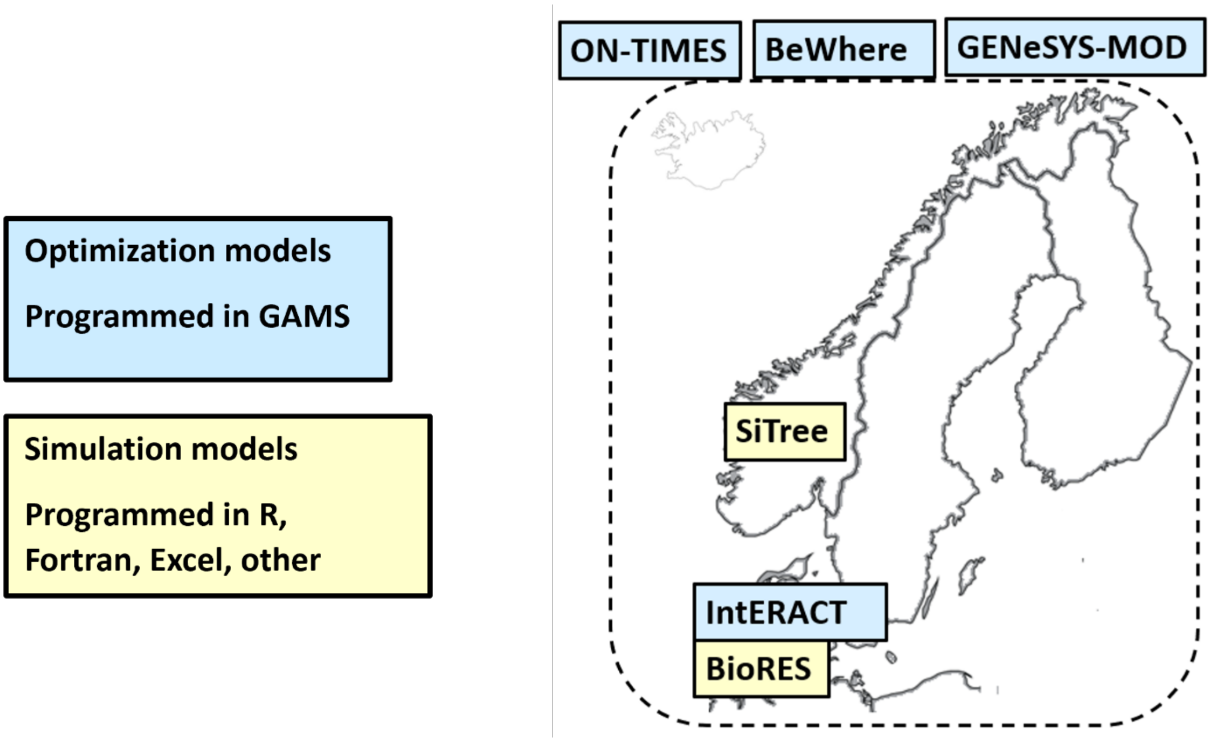


Figure 2-4: Geographical coverage, model type and language of applied models

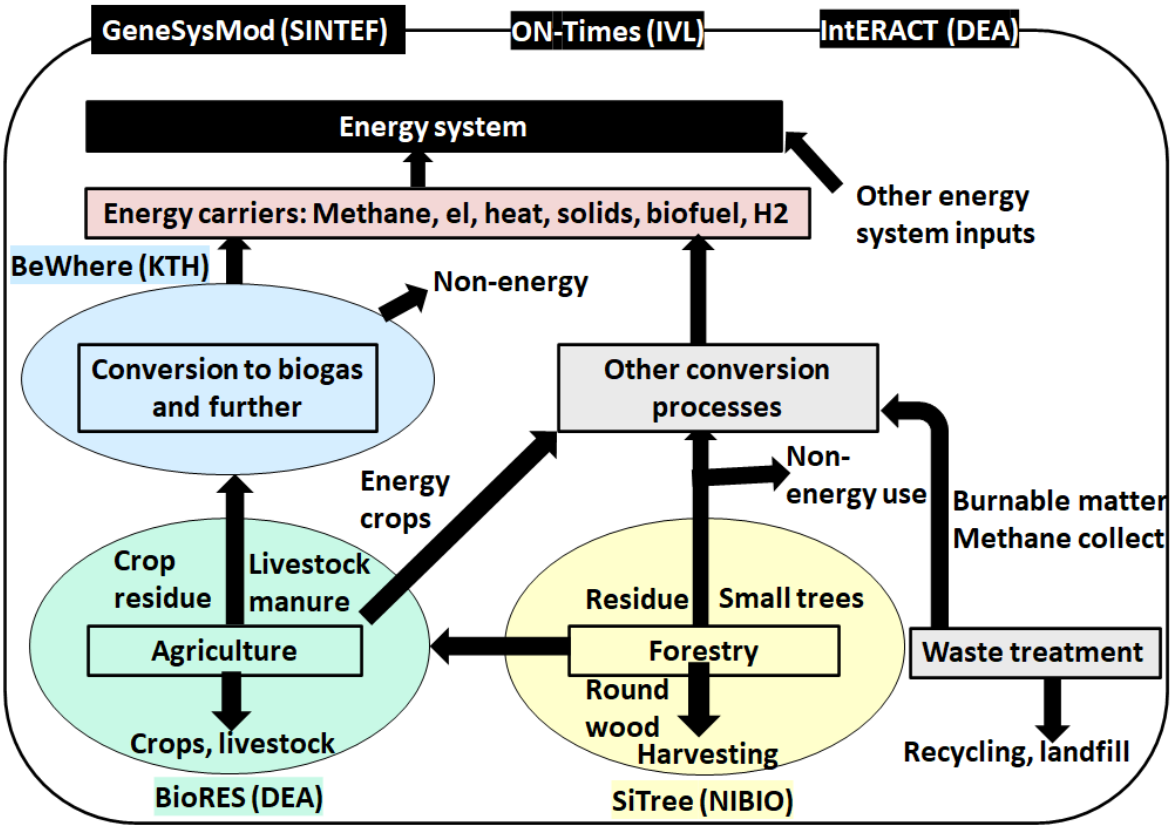


Figure 2-5: Sectors and energy carriers of applied models

The sector specific models are important tools that can be used in the improvement of general energy system models, such as ON-TIMES, GENeSYS-MOD and IntERACT (TIMES-DK). General energy system models can benefit from soft-linking to sector specific models, tools or methods such as:

- The outcomes from BeWhere provide the optimal geographical location and size of biogas production plants with respect to biomass feedstock and demand location. These outcomes can serve as basis for techno-economic data assumptions of investment options for new biofuel production plants.
- BioRes includes agricultural, forest and marine production sectors and has been created to build scenarios for Danish biomass resources and use (including manure). Results from the model can be used as basis for assumptions for availability, import and export of biomass in Denmark to be used in IntERACT (TIMES-DK). If BioRes were further calibrated for other Nordic countries, outputs from it could be used by GENeSYS-MOD and ON-TIMES.
- SiTree can be used to improve the estimated datasets on available wood residues in Norway that are currently used by the general energy models. If SiTree could be further developed to include other Nordic countries, it could provide a complete database on forestry residue availability for the overall energy models applied for the whole Nordic region.
- General energy system models include assumptions on the biomass potential in the Nordic countries. These assumptions could be adjusted by incorporating key aspects affecting the biomass potential from agriculture from a LCA perspective. Climate impact indicators and the associated environmental performance obtained from different LCA frameworks (such as

RED, EPD and PEF) could be included for the key agricultural biomass streams in the general energy system models.

ON-TIMES and GENeSYS-MOD are two energy system models that depict all the Nordic countries. Despite their similarities, results from the two models could be compared and benchmarked to each other, with regards to biomass use in different sectors for the same level of CO2 emissions abatements in the Nordic countries.

In Box 1 there is a discussion if ON-TIMES and TIMES-DK should be considered one model – i.e. the TIMES model – or two different models.

Box 1: Model vs. model-generator

In WP1, there are two instances of the TIMES model included: ON-TIMES for the whole Nordic area, and TIMES-DK for Denmark. Should this be considered as one "model" (TIMES), having two different datasets, for the Nordic area and Denmark respectively? Or are ON-TIMES and TIMES-DK two different models? When considering ON-TIMES and TIMES-DK, there will be many differences. The included equations are different, the input data are different, and most of all: they are attempts to represent totally different systems. So, even though they are built up through the TIMES software, ON-TIMES and TIMES-DK can be considered two different models – whereas the TIMES software can then be considered to be a model generator rather than a model. But could not the same be claimed also e.g. for GENeSYS-MOD and any other "model"? Different datasets are used within the same model when this is used to represent different systems. This is also true. An important nuance is that the TIMES software is developed with the aim of being able to build up the representation of very different systems. The term "model generator" will therefore fit better to TIMES. An additional conclusion is that the term "model" is ambiguous. In general, a model can be considered a representation or simplification of something which is more complex, with the aim of being useful e.g. in terms of prediction. However, that representation exists of several parts, encompassing at least by:

- The formal – typically mathematical – representation
- Its quantification – the dataset, also including parameter calibration

Depending on the context, it can be useful to discuss "a model" in terms of the first bullet, the second bullet, or both.

3. Project outcomes

3.1. Project outcome types

There are several types of outcomes from WP1. Consider for instance the aims of the programme, which are illustrated in Figure 1-1. Some of them are dealt with in specific sections of this report. For instance, we point out promising new research in Section 4 and provide inputs to the updating of NECP in Section 5. Achievements for some of the goals cannot be documented easily in a report, such as strengthening of competence and cooperation. Those aims are still very important, and the achieved results for this will have impacts in the future.

This chapter deals more specifically with the work specified within the individual contracts for each research partner in WP1, related to improvement of respective methods, models, and data.

3.2. IVL

Biomass potential in the Nordics

In this study, we carried out an extensive literature review on the potential of various types of agricultural biomass and key aspects affecting the potentials in the Nordics and environmental impacts of the agricultural biomass. In the following sections, the results of our literature review are presented. For further extensive details see Appendix.

A number of studies have estimated the future total potential of biomass from the agricultural sector see e.g.,[54], [55] or [56]. In this first part of the work, we build on previous studies, mapping the work completed at IVL and broadening the scope from Sweden to a Nordic perspective see Table 3-1. IVL has earlier performed studies considering theoretical, economic, and environmental limitations to biomass potential from agriculture. The result from the reviewed material from IVL is an estimated potential of 1.2-1.5 TWh/yr for Sweden. If technical limitations are overlooked for straw, there could be an additional potential of 10-16 TWh/yr. IVL has also conducted two local estimations, one for Gothenburg City [57] and one for the municipality Grästorp [58] in southern Sweden. It was there found that the municipality Grästorp could, with the theoretical potential, cover the energy demand in the region in comparison to Gothenburg, which due to lacking agricultural land, could not. This demonstrates the differences in potential when narrowing down to a local scale where the energy-demanding cities cannot provide enough biomass for their energy demand. Two assessments were made for the total Danish energy potential in the reviewed literature and appreciated to 44-50 TWh [59] and 49-51 TWh [60], respectively. Both studies excluded energy crops. In the reviewed Norwegian literature, the entire biomass potential was estimated to be 2,2 TWh [61] and 2,5-5,5 TWh [62]. Out of the total potential, the agricultural contribution was assumed to be limited based on the small share of agricultural land available in the country.

Table 3-1: Estimated biomass potential in the reviewed literature from agriculture in the Nordic countries.

Author	yr	Country	Potential
Astrup, T., Tonini, D., Hamelin, L., & Wenzel, H.	2011	Denmark	176 -184 PJ
Belhaj, M. et.al.	2010	Sweden	1.5 TWh Sweden/yr
Börjesson, P.	2021	Sweden	14-22 TWh until 2030 21-33 TWh until 2050
Carlsson, A. et.al.	2014	Sweden	7 TWh in 2020
Danish Energy Agency	2020	Denmark	160-180PJ
Egnell, G	2008	Sweden	ca 30 TWh
Fossilfritt Sverige	2021	Sweden	9-14 TWh 2030 13-23 TWh 2045
Hjort, A.	2019	Sweden	1.2-22 TWH/yr
Hunhammar, S. et.al.	2021	Sweden	6.6-9.2 TWh to 2045
IVA	2019	Sweden	35-40 TWh
O'Sullivan Freltoft, A. & Græsted Jensen, I	2021	Denmark	Straw: 19.6, 26.9, 24.9 PJ Grass: -, 19.9, 18.2 PJ Manure: -, 2.0, 2.1 PJ
Scarlat, N. et.al.	2011	Norway	9-19.8 PJ
Scott Bentsen, N et.al.	2016	Sweden/Denmark	65 EJ/yr
Svebio	2020	Sweden	54 TWH
Tonini, D et al.	2015	Denmark	5600 Mkg ww/yr
Trømborg, E	2015	Norway	8 PJ
Westlund, Å. et.al.	2019	Sweden	30-37 TWh /yr

The findings correspond to the report by Pöyry [63], which also takes into account all Nordic countries. The current potential for agricultural biomass for energy production is greatest in Sweden, but future biomass production has a larger potential in Denmark. In the Danish case biomass from agriculture is mainly found as a side flow to animal produce. A limitation to the future potential could be less intense animal production and degrading soil quality.

On average, the estimated potential of biomass production for energy purposes in Sweden was higher in non IVL reports. For example, Kungliga Ingenjörsvetenskapsakademin (IVA) [64] sees a crop production that contributes 35-40 TWh, similar to Westlund, Å. et al. [65], who predict a technical or practical potential of 30-37 TWh. Furthermore, Andersson and Lundin [66] had foreseen an economic potential of 30 TWh by 2020.

Key aspects affecting future agricultural biomass potential in the Nordics

In a future perspective, the potential is expected to increase. The estimated increase is in Sweden around 9-14 TWh [67] or 14-22 TWh [54] by 2030, with a similar or slightly bigger addition until 2045 and 2050 [68]. Börjesson [54] revised his forecast from 2016 by decreasing it by 20 % due to reduced potential for energy crops. One Danish study [69] estimated the future potential of specifically straw and grass to approximately 5,4 TWh each by 2030. Whereas the straw potential would increase to 7,5 by 2050, the grass potential would decrease 5 TWh. The future Norwegian potential was assumed to be limited and have little influence on the energy supply for the country [54, 67].

As Table 3-2 presents, there are several types of agricultural biomass sources in the Nordics, but their availabilities vary in each country. For the full matrix and further information see, the appendix.

Table 3-2: Identified biomass sources from agriculture in the reviewed literature from the Nordics

Country	Biomass sources
Sweden	Blast, Cereals, Chaff, Crop residue, Grass, Hemp, Legumes, Manure, Oilseed, Organic waste, Potatoes, Rapeseed, *Rörflen*, Salix, Sly, Straw, Stubble, Sugar beet
Denmark	Straw, Grassland, Industrial residue, Waste, Manure, Animal fat, Rapeseed, Willow, Meat and Bones
Norway	Straw, Crop residues, Energy crops

The main biomass source is straw from cereal production, followed by manure, legumes, energy crops and grasses. Blast, sly and food waste were also recurringly mentioned as biomass sources. Future straw production is predicted to be influenced by climate adaptation measures such as a change in diets and reduced consumption of animal products. Similar effects could also impact the manure waste flow.

Competition for agricultural land, mainly with food production, was a barrier to future biomass production that reoccurred in the reviewed literature. Other limitations to the Swedish potential were inefficient distribution systems and infrastructure, lack of policy tools, climate change, price on competing energy sources and revenue for biomass production. The main barriers found in a Danish context were that of limited land area within the country and potential future crop yield. Compared to Sweden and Denmark, the Norwegian biomass potential is significantly limited to the lack of agricultural land. Other barriers recognised in the Norwegian literature were that of a relatively low price on competing energy sources such as fossil fuel.

However, the result from the literature review is not directly applicable to the ON-TIMES model. As is seen in Table 2-1 in 2.2.1. about the ON-TIMES model there is already some biomass sources listed in the data set. The result from the literature review would require further disaggregation for direct application, but this was not available in a comparable way. Therefore, the gathered list of agricultural biomass sources could be mapped against the current data set to complement the input. But, in future studies, it would be advantageous to divide the potential between different crops to further complement and develop already existing data.

Environmental impact assessment of agricultural biomass

As it was mentioned, seven types of agricultural biomass sources are modelled in the ON-TIMES model: rapeseed, maize, sugar beet, grass, straw, deep litter, and slurry. These sources are assumed to be used as feedstocks to produce bioenergy. In the TIMES model, the GHG emissions from the biomass are set as zero. However, from a life cycle perspective starting from cultivation, which is the 'cradle' of the supply chain, biomass requires energy and resources to grow. To produce biomass, it needs cropland, fertile land, fertilisers, pesticides which in turn requires fuels to operate. These processes are considered as the upstream of biomass. In the TIMES model, only emissions from LULUCF sector, fuel use in machinery within agricultural sector are accounted for at a national and aggregated level. Hence, these data are not specific for different biomass sources and other upstream emissions such as production and application of fertilisers are missing. This contrasts with oil and gas production, whose upstream CO_2 emissions are accounted for. There is, therefore, a data gap in biomass assumptions that can be improved.

Life Cycle Assessment methodology

A life Cycle Assessment (LCA) can be used as a tool to account for the environmental impacts of a product or service. A product's life cycle generally consists of several stages, e.g., raw material extraction, production process, use stage, and end-of-life. Despite the main principle of an LCA being the same, there are many types of LCA frameworks one can apply when calculating a product's environmental impact.

LCA framework according to the ISO 14040/44 standard [70, 71] is one of the most fundamental and well-known frameworks. Environmental Product Declaration (EPD), which is an independently verified document to communicate environmental information, is also another example of an LCA framework. In the context of biofuels, the recast of the Renewable Energy Directive (REDII) [72] which is the European Union's regulatory framework that aims to increase the use of renewable energy, is often mentioned. The REDII requires fuel producers to increase the use of renewable energy to reduce the amount of GHG emissions from fossil fuels. The calculation of GHG emissions saving by using a certain type of biofuel is based on a life cycle perspective. The main differences between the three mentioned frameworks lie in their allocation approach when a process produces more than one product or when it involves a recycling process. The ISO14040/44 allows a first-hand approach known as system expansion or substitution, which considers the credit of co-products being used in another process to substitute the use of primary material. The EPD framework does not allow system expansion but suggests that allocation based on physical or economical relationship can be used if an allocation cannot be avoided. For the REDII framework, more specific rules apply, where allocation based on energy value shall be used. In addition, The EPD and REDII framework does not allocate any emissions to waste or residue, while this choice is up to the practitioner when applying only the ISO14040/44 standard.

The study

We have carried out a literature study to collect the environmental impact for five out of seven types of biomasses — namely rapeseed, maize, sugar beet, grass and straw. However, the results from the literature search appeared to be quite limited as the scope is narrowed to different Nordic countries. Few of the articles reviewed aim to solely calculate the biomass' environmental impact but perform the calculations accompanied by the production of biofuels or food. Hence, it is not easy to extract the specific result for the studied biomass. Furthermore, many studies have investigated a specific situation in their system, such as the substitution of fossil fuels to biomass or the crops grown or used for a specific purpose e.g., a combined food and energy system. Therefore, the data is not entirely applicable to this study and as such only a few pieces of literature can potentially be used in the ON-TIMES model. Sugar beet is included in the literature search, but no relevant studies were found. The results from the literature study are shown in Table 3-3.

Only Global warming potential (GWP) and Eutrophication potential (EP) for each type of biomass are included in Table 3-3. The initial ambition of this study was to investigate several environmental impacts of the biomass. However, the only environmental impact indicators common to several of the included studies were GWP and EP, and as such these are the only types of impacts used in the results of this study. Several of the studies included a greater number of indicators, but since these were not used in the other studies or were measured using different methods, the data could not be compared to the other frameworks and was hence omitted.

Table 3-3: Environmental impact indicators for different types of agricultural biomass

Biomass source	Global warming potential (GWP100) (gCO2eq/kg DM)	Eutrophication potential (EP) (gPO4eq/kg DM)	Applied framework	Reference
Straw				
NO (wheat straw)	37.4-43.4	-	REDII	[73]
DK (wheat straw)	152	0.61	EPD International	[74]
Grass				
SE	136-178		ISO14040/44	[75]
DK (grass-clover)	354	2.04	EPD International	[74]
DK (ryegrass)	410	1.76	EPD International	[74]
Maize				
DK	315	1.44	EPD International	[74]
Rapeseed				
NO	960-1240	10.7-16.1	ISO14040/44	[76]
DK	638	-	RED	[77]

Table 3-3 shows that the results from the LCA studies give different values depending on which framework is applied. Apart from the main difference between the three frameworks (described previously), some different methodologies relating to agricultural models are not specifically described in any framework. For example, the N2O emission from soil can be calculated based on the IPCC method or DNDC tool (Denitrification-Decomposition), how the change in Soil Organic Carbon (SOC) is assumed and calculated etc. In the TIMES model, the effect of LULUCF (carbon source and sink) in different Nordic countries have already been included. As the results from Table 3-3 included the emissions from SOC change, the SOC change effect will therefore be accounted twice if it were to be integrated in the TIMES model. Furthermore, the input materials may not be accounted for the same way. In the case of Svanes et al. [76], the impact from capital goods such as buildings and machinery are included, which explains why their result is higher than the one calculated by Thers et al. [77].

However, there are also some similarities in the calculation between the literature used in Table 3-3. Firstly, they all assume that biogenic CO2 is climate neutral, as the same amount of CO2 is being removed and released into the atmosphere. Secondly, the effect of land-use changes both directly and indirectly is either not considered or assumed to be irrelevant as there has not been any change in land use. Considering that there are more differences than similarities, the results in Table 3-3 may not be suitable to use in the ON-TIMES model. This also means that there is a need for harmonisation between the LCA frameworks. Furthermore, the risk of double counting emissions from LULUCF sector and energy use within agricultural sector will make the LCA results not compatible with the TIMES model.

The way the results are presented is another reason why the findings in the table might not be appropriate to incorporate in the ON-TIMES model. Ideally, data would be separated into CO_2 emissions and non-CO_2 emissions to suit the model. However, most LCA studies typically express the climate impact in terms of CO_2-equivalent (CO_2-eq). Among the reviewed articles, such information can only be extracted from the study done by [73]. European data from a study done by JEC (JRC-Eucar-Concawe) were extracted to show the level of emissions from parts of the upstream processes by three types of GHGs: CO_2, N_2O and CH_4, as a complement to the result [78]. See Table 3-4.

Table 3-4: GHG emissions arise from crops emissions and production of fertilisers and pesticides, representing European countries. Note that this is only part of GHG emissions in the upstream processes, it does not represent a complete calculation of biomass production

Biomass source	GHG emissions (g/kg biomass)			Reference
	CO_2	N_2O	CH_4	
Straw				
NO	2.61	6.30E-05	5.67E-03	[73]
EU	11.68	0	0	[78]
Maize EU	81.25	0.78	0.04	[78]
Rapeseed EU	215.73	1.66	0.11	[78]
Sugar beet EU	29.60	0.22	0.01	[78]

Even though the data collected in Table 3-4 does not include calculations for, e.g., the use of machinery in the agricultural processes, it could still help develop the ON-TIMES model. The data could be integrated into the model or used as an additional analysing tool to calculate the amount of GHG emissions that the biomass gives rise to at the minimum level. It is possible to exclude energy consumption because the TIMES model has already considered the impact of energy use within the agricultural sector. Having more detailed data when modelling the energy sector will help estimate the release of GHG emissions and future mitigations required to reach a net-zero. By attaching a GHG emission factor to biomass can make the ON-TIMES including the value of this in the optimisation and thereby choice of investments. If there is put a price on the upstream GHG emissions from biomass this can influence the choices of the model.

Eutrophication impact and other environmental impacts that are not associated with CO2 emissions can in theory be integrated in the TIMES model as they are not connected to the existing data in the model. Hence new data can simply be added for different biomass sources. This additional environmental information associated with the use of biomass can be integrated in the energy system model as scenario options for those who are interested in more details of the biomass.

There is a study done by Volkart et al. [79] that investigated the integration between LCA indicators and the energy system model (Global Multi-regional MARKAL) without double counting the impact of the energy system, which can be relevant to study further. Volkart et al. selectively excludes energy input emissions in the life cycle inventory data to avoid a double counting. This approach can be applied to the problem we have in this project, but it would require a comprehensive life cycle emission data which has proven to be a challenge in the context of the Nordic region. See also the discussion in Box 2.

Box 2: LCA estimates in energy system models

In the energy system analysis, emissions are typically accounted within different sectors where they actually occur. LCA, on the other hand, focuses on a specific product or service and takes into account the emissions that occur along its life cycle i.e., from *cradle-to-grave*. This poses a challenge to integrate a life cycle perspective into the energy system models as they can cause a conflict to each other. Examples of the conflicts are the CO2 emissions and removals in the LULUCF sector that will lead to a double counting issue when integrating the calculation of SOC change from an LCA. The emissions from energy use in agricultural machineries will also be accounted for twice as they are already accounted for in the agricultural sector. In addition, there is no consensus in whether the emissions from infrastructure, production of machineries, and energy use to operate within buildings should be included in an LCA calculation. These emissions, however, may have already been included in the energy model under construction and vehicles sector. Since LCA and energy system model are two ways of accounting for emissions, it is questionable whether they can be integrated into each other.

3.3. KTH

This study explores the biogas production from the agriculture sector using GIS spatial approach and identify the importance of integrated approach in a CLEWs (Climate-Land-Energy-Water systems) approach. The role of biogas in decarbonising the Nordic' energy sector, land-use emissions, and avoided emissions from the agriculture sectors are also taken into account. As mentioned previously, the BeWhere model incorporates the techno-economic, spatial and temporal components to optimise location, capacity, technology and timing of energy conversion sites. Detailed information throughout the supply chain is required in this study. In the study, we developed a BeWhere modelling framework, which optimises renewable energy systems through cost minimisation for the welfare of the region. Feedstock production data, availability of feedstock for biogas production, selection of conversion technologies, techno-economic parameters of AD plants, and final conversion technologies (CHP and biogas upgrading) are estimated. Feedstock supply, and derived biogas/biomethane, bioelectricity, bioheat, and bio-fertiliser are quantified and mapped spatially in the region. The demand of energy (esp. electricity, transport fuel, natural gas, heat) in the region is also estimated using a simple regression model. This will help to estimate how much energy demand can be substituted by biogas derived energy carriers, e.g. biomethane and bioelectricity. Modelling outcomes that can be generated from BeWhere studies are technology selection, location, plant set up and quantity of bio-products. The model identifies the most-cost effective technology at each plant and total bio-products generated. It will determine the supply location to provide feedstock for the biogas system.

Biomass feedstock from crop and livestock production in the Nordic Region

Crop and livestock production plays a vital role in the agriculture sector in the Nordics. There is an enormous potential for bioresources (i.e., crop residues and manure), which can be converted into biogas and other energy carriers in the region. It is essential to find the spatial distribution of biomass feedstock, which enables to find the optimal size and location of biogas production facilities, among other things.

In 2020, the total number of heads is estimated to be 68,935,456 heads in the Nordic countries (See Table A-2). The major contributors are: chicken, pig, and cattle, contributing together to 90% percent of the total number of livestock, as described in Figure A-1. The majority of the livestock concentrates in the southern Sweden and Denmark, while Iceland and the northern Norway, northern Finland, and northern Sweden have the lowest numbers for every visualised data, see Figure 3-1.

The analysis shows that the Nordic countries have produced 30,356,000 tonnes in 2020 (see Table A-3). Wheat, barley, and sugar beet contribute together with almost 75% of the total number (see Figure A-2). Most of the crop production concentrates in the southern Sweden, southern Finland and Denmark, while Iceland and the northern Norway, northern Finland and northern Sweden have the lowest numbers, for every visualised data, see Figure 3-2.

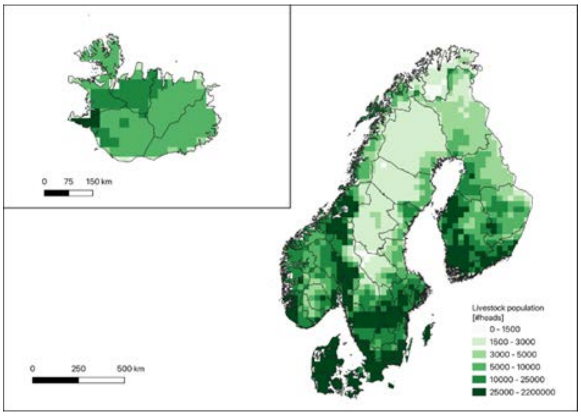


Figure 3-1: Livestock population in the Nordic countries in 2020

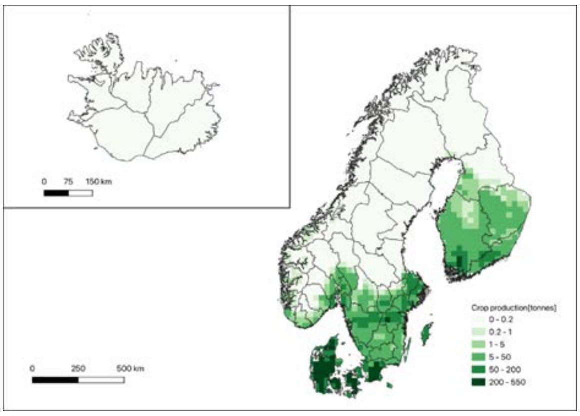


Figure 3-2: Crop production in the Nordic countries in 2020

Using the residue to crop ratio (RPR) and amount of manure produced by livestock per day, biomass (residues and manure) for biogas is obtained in each grid cell (also, see Table A-4 and Table A-5). Figure 3-3 and Figure 3-4 depict the total manure and crop residues available in the Nordic countries.

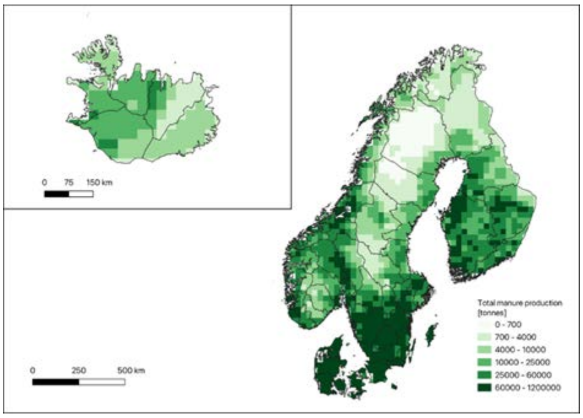


Figure 3-3: Total manure in the Nordic countries in 2020

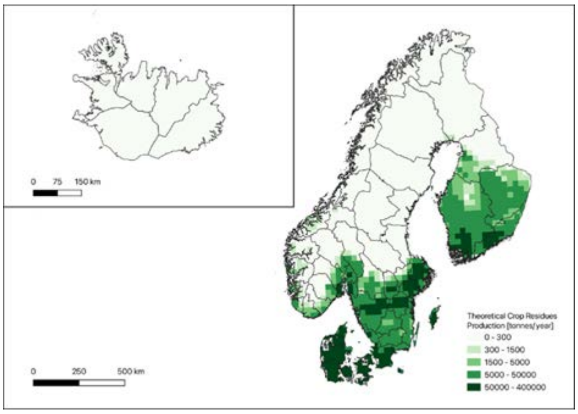


Figure 3-4: Theoretical crop residues production in the Nordic countries in 2020

(a)

(b)

Certain amount of crop residues should be left in the farmland for maintaining soil quality [80]. In this study, we consider the sustainable removal rate (SRR) as 40%. Figure 3-5 visualises the total practical crop residues available for biogas production in the region.

Biogas production from agriculture residue and manure in Nordic countries

The practical biogas potential in each grid is calculated using the equations provided in the appendix. All the calculations are done separately for crop residues and manure and summed up together to find the total biogas potential in each grid. The methane content in the biogas is considered as 60% and the LHV of biogas is taken as 6 kWh/Nm^3. Residues and manure potential are also calculated at the grid level and later summed up together. Bioelectricity in the grid level is calculated considering the CHP plant efficiency as 30% and bioheat is calculated using the heat to power ratio 0.6.

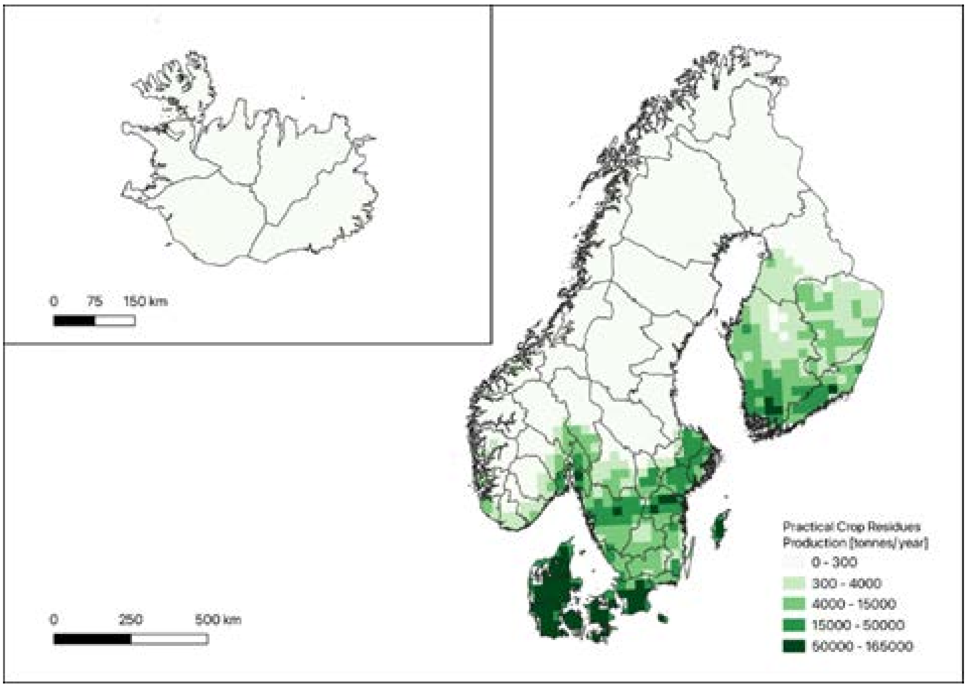


Figure 3-5: Practical crop residues production in Nordic Countries in 2020

Table 3-5 is the total biogas potential in each of the Nordic countries, which is calculated by summing up the values from the grid. This study considers the choice of different technologies, which can convert biogas into different forms of energy, e.g. CHP plants (bioelectricity and bioheat) and biomethane upgrading plants. The BeWhere model selects the suitable technology and conversion pathways as per the modelling parameter and constraints.

Table 3-6 summarises the total biogas potential in the region. The data are projected to 2020 using the available FAOSTAT data, since the crop residues data are available only until 2015 and manure data are available only until 2010. The raw biogas potential is 151.93 PJ. If it is upgraded into methane, then the biomethane potential will be 89.83 PJ. The raw biogas can be used in CHP plant for power and heat production. The total bioheat and bioelectricity potential will be 75.85 PJ and 45.5 PJ, respectively.

Table 3-5: Total potential of different technologies in each Nordic country in 2020

Country	Agriculture residue and manure (million tonne/year)	Biogas (PJ/year)	Biomethane (PJ/year)	Bioelectricity (PJ/year)	Bioheat (PJ/year)
Denmark	38.88	70.91	42	21.27	35.46
Finland	14.83	24.72	14.62	7.42	12.36
Iceland	1.41	1.49	0.9	0.45	0.75
Norway	13.57	14.84	8.84	4.45	7.42
Sweden	23.90	39.74	23.48	11.92	19.87
Total	92.58	151.7	89.83	45.5	75.85

Table 3-6: Total energy potential from crops residue and manure in 2020 in all Nordic countries

Technologies and energy production		PJ	TWh
AD plant	Biogas	151.7	42.14
Upgrading plant	Biomethane	89.83	24.95
CHP plant	Bioelectricity	45.5	12.642
	Bioheat	75.85	21.069

After reprojecting the data from FAO in a new grid, the results for the total biogas potential from manure and agriculture residues are processed on QGIS. Figure 3-6 shows the total biogas potential in each grid cell in the Nordic countries. Table A-6 and Table A-7 provide biogas from the specific feedstock (manure and crop residues)

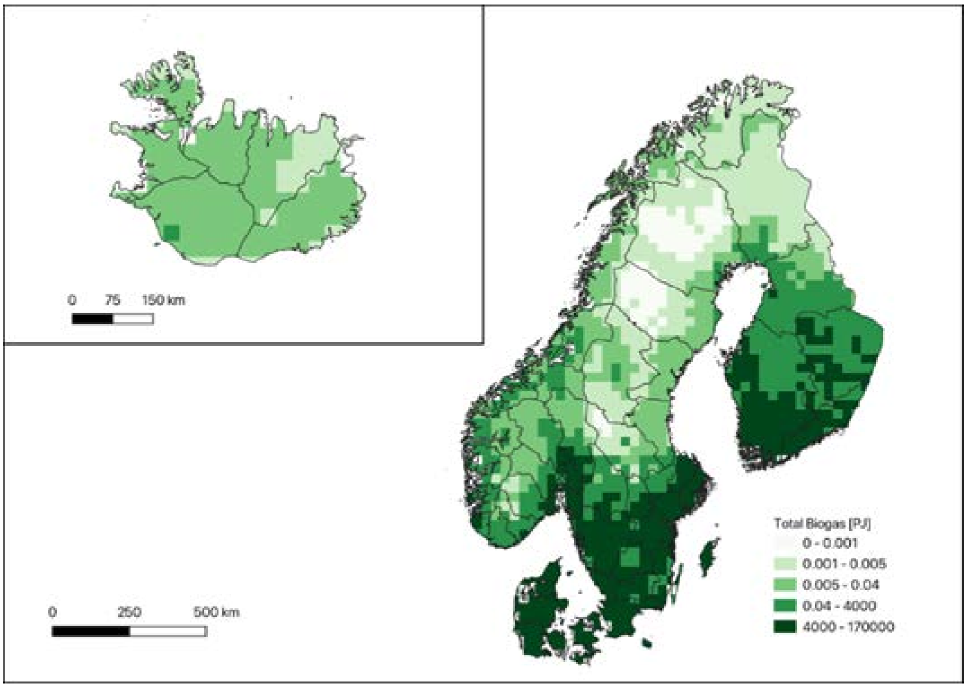


Figure 3-6: Total biogas potential from agriculture residues and livestock manure in the Nordic countries in 2020

The role of Biogas in decarbonising the Nordic countries' energy sector

Biogas can contribute to substituting fossil fuels in the region. As seen in Table 3-7, the total biogas production was 25.2 PJ. The estimates show that we have only harnessed around 17% of the total biogas potential. Utilising the full potential, around 3.3 % of the total power can be provided by bio-based bioelectricity and 14.4% of the district heating energy demand by bioheat. Around 48% of natural gas can be replaced by biomethane (See, Table 3-7).

Table 3-7: Biogas production potential, energy consumption, and the share of biogas-based energy in the Nordic countries in 2020

	PJ	The share of biogas/biomethane/bioelectricity
Total biogas energy potential *)	151.7	
Current biogas production in 2019 [81]	25.2	
Power Consumption	1386.504	3.3%
Natural gas consumption	187.4981	47.9%
Transport fuel consumption	860.0144	10.4%
Energy consumption in district heating	528.2504	14.4%
Cooking fuel consumption	55.907	36.9%

*) From our calculation

The total bioelectricity potential is around 45.5 PJ, which can substitute 11.9% of the non-renewable energy in the region (see Table 3-8).

Table 3-8: Electricity consumption (in PJ) from different technology [82] and bioelectricity potential in the Nordic countries in 2020.

Hydro	Wind	Solar	Solid biofuels	Other renewables	Non renewables	Bioelectricity potential (our calculation)
828	172.8	14.4	86.4	36	381.6	45.5

In the Nordic countries, emissions from the transport sector are high due to fossil oil based transport systems. Around 11 % of fossil oil can be replaced by biomethane. The total diesel consumption in the Nordic countries was 626.5 PJ in 2020 [83] and the corresponding emissions were 55.13 million tonnes CO2 [84]. Biomethane can substitute around 14.3% of the diesel consumption, thus reducing emissions in the region.

Land-use emissions, avoided emissions, water and energy use in the agriculture sector

The total estimated emissions from livestock population are 30 million tonnes of CO2eq, in 2010, while crop production contributed to 13.8 million tonnes of CO2eq, in 2015. GHG emissions from the agricultural land are estimated using secondary data (See Table A-10, Table A-11, Table A-12).

The management of the digestate is the second important aspect that determines biogas sustainability. The use of open storage results in uncontrolled methane, nitrous oxide, and ammonia emissions while closed storage aids in the reduction of emissions. The nutrient quality in the bio-digestate is calculated and compared with the current fertiliser demand in the Nordic (see Table 3-9).

Table 3-9: Current fertiliser consumption in crop production in the Nordic countries in 2019 and bio-digestate potential

Particulars	Bio-digestate in tonnes (From our calculations) (kilo-tonnes)	Total fertiliser consumption, (kilo-tonnes)	Comparison (Biodigester/Total fertiliser consumption)
N	692.5	671.6	1.03
P	283.3	111.2	2.55
K	464.3	187.9	2.47

The study finds that bio-digestate can replace the current fertiliser consumption. The nitrogen content in the available bio-digester is almost the same as the current demand in 2019. Potassium and phosphorus are more than twice the demand. This would also contribute to reducing emissions from the production and application of fossil-based synthetic fertilisers.

We need water and energy for crop production. The water usage in the agriculture sector has the higher value in Norway, which used 0.845 billion cubic meters of water in 2004. Table A-14 (in Appendix) summarises the energy and water consumption in agriculture in the five countries.

Scenarios and exploration of future biogas production

When it comes to the change of crop and livestock production, two FAO scenarios [85] can be incorporated in the BeWhere Model: "Towards Sustainability (TS)" and "Stratified Societies (SS)", for both livestock and crops, considering all the Nordic countries and the CLEWs aspects. The TS scenario represents the best-case scenario, with minor temperature changes and the lowest CO2eq concentrations. On the other hand, the SS is the worst-case scenario with the higher temperature changes and CO2eq concentrations.

CO2 concentration, RCP, and temperature change contribute to changes in the number of livestock and crop production from 2020 to 2050. In general, in the TS scenario, the number of livestock decreases, and the crop production increases slightly. On the other hand, in the SS scenario both livestock and crop production have a larger increase. Table A-16, Table A-17, Table A-18 provide the livestock and crop production from 2015 and 2050 in two Scenarios.

Biogas production potential has been estimated in three scenarios (see Table 3-10). It is observed that in the FAOSTAT scenario, the biogas potential has a significant increase from 2020 to 2025, and over the years, the potential is almost stable. In the CLEWs -TS scenario, the biogas potential is not having a significant variation over the years. But, in CLEWs - SS scenarios the biogas potential keeps on increasing over the years and has the highest potential in 2050.

Energy demand projections that the transport fuel consumption is seems to be increasing in the Nordic region over the years. Therefore, replacing fossil fuels with biomethane is quite possible by utilising the biogas potential in Nordic countries. It is not possible to fully replace fossil fuels but still a significant contribution can be made by biogas/biomethane. Following the CLEWs-SS scenario, it is possible for the biogas to produce 122.46 PJ biomethane (60% of biogas) from the upgraded plant in 2050. Which can replace around 13% of the transport fuel consumption. Or else the biomethane can be fed into the natural gas grid and can replace around 55.7% of natural gas consumption in 2050. In the CLEWS SS scenario, the crop production is kept on increasing over year.

Table 3-10: Total biogas potential in different scenarios in Nordic

	FAOSTAT Reference scenario			CLEWs- TS scenario			CLEWs - SS scenario		
Year	Manure (kilo ton)	Biomass (kilo ton)	Biogas (PJ)	Manure (kilo ton)	Biomass (kilo ton)	Biogas (PJ)	Manure (kilo ton)	Biomass (kilo ton)	Biogas (PJ)
2020	81572.8	11011.5	151.7	84656.2	11036.9	153.8	81263.9	13332.3	170.1
2025	78090.4	19840.1	181.7	83500.5	10931.7	152.8	78998.8	14461.1	177.9
2030	76585.8	20077.0	182.2	81774.2	10824.9	151.8	77069.0	15407.3	184.4
2035	81572.8	20313.9	182.7	79684.8	10918.8	152.4	76633.5	16140.6	189.2
2040	75081.2	20550.8	183.2	77396.7	11138.4	153.8	77070.0	16752.2	193.1
2045	73576.7	20772.5	186.8	75276.3	11401.0	155.6	77881.3	17310.8	196.6
2050	70028.3	21033.7	184.1	71557.6	11974.6	159.6	79631.6	18493.0	204.1

Developing an integrated assessment framework for biogas production in the Nordics: Linking CLEWs aspects in the BeWhere model

In this project, KTH has developed a modelling framework for integrated assessment of biogas production from the agriculture sector, i.e. crop and livestock production. Spatial assessment of crop and livestock population is done at the grid level, which provides the basics of feedstock supply. We have compiled techno-economic parameters (investment and operational costs) of three technologies, viz. AD plant, CHP, and upgrading technologies. The costs of feedstock, transport cost, cost of production of biogas are prepared in the modelling dataset. We also prepare the emissions from agricultural field while producing livestock and crop. The final demand of different fuels such as natural gas, electricity, and transport fuels are estimated. The price and emissions factors of avoided energy products are also done. The model would determine the optimal location, size, and type of the technologies based on the feedstock supply, energy demand, costs, and prices, policy instruments such as subsides and carbon tax. All revenue streams and emissions need to be accounted and considered as input data for the model.

The water-food-energy (WEF) nexus is central to sustainable development. KTH has been working on how climate, land use, energy and water can be interlinked while meeting the food, energy, and water demands using a CLEWs modelling framework. In this resource-constrained world, demands of all three are increased due to economic growth, population rise, urbanisation, and changing dietary patterns. The agriculture sector requires freshwater for crop production and energy for the cultivation and transport of food commodities. Additionally, the use of nitrogen fertiliser and methane emissions from the sector contributes in GHG emissions, thus posing threats to climate systems. Our work proposes to further research in developing the inextricable linkages between these critical domains, which requires an integrated approach to ensuring water and food security, and sustainable agriculture, and energy production in the region. The impact of climate change in crop production, the use of fertiliser, energy and water, and agricultural practices need to be considered in the integrated model.

Finally, the project provides a sound basis for integrating CLEWs aspects into the BeWhere techno-economic optimisation model. The CLEWs framework assists the exploration of interactions between (and within) CLEW systems via quantitative means. As the model does not optimise the benefits at the plant levels - thus, welfare aspects such as security supply, prices, and environmental costs are significant in the modelling of bioenergy systems. Its multi-institutional application to the case of Nordics would help in promoting the security food, energy, and water systems. In this work, we have provided a few of the CLEWs framework in perspective to its application in the Nordic context.

3.4. SINTEF/NIBIO

The results of a linear energy system model are to a large extent dependent on the dataset that is used by the model. Our first research question is *"How can we take advantage of the results from sector models specific for the bioenergy sector, such as results from resource potential calculations to improve the quality of the analysis of a complete energy system?"*.

To be able to address this question, first a solid understanding of what is represented in each of the categories concerning biomass in GENeSYS-MOD is needed. An important step of the work was hence to gather information on the definitions of the different biomass resource categories. A second step was to understand the underlying data sources for both the benchmark year and for the projections of the biomass potential and costs over time. Then, the quality of the datasets could be analysed, and suggestions formulated on potential for improvement.

The dataset analysed in this work consists of six different biomass resource categories labelled: Grass, Wood, Roundwood, Residues, Paper&Cardboard and Biogas. Table 3-11 describes in detail what types of biomasses are included in these different categories.

Table 3-11: Categories for biomass availability and respective prices in the current dataset in GENeSYS-MOD.

Biomass Resource Types	Subtypes	2020-price, M€/PJ
RES_Grass	Verge grass	3.06
RES_Wood	Prunings, landscape care wood, woody perennials, post-consumer wood	3.24
RES_Roundwood	Additional harvestable roundwood, roundwood, stemwood	13.28
RES_Residues	Saw-dust, MSW (excluding landfill, composting, recycling), sawmill by-products (excluding sawdust), straw, grass cuttings from abandoned grassland, other industrial wood residues, grassy perennials, primary forestry residues	3.60
RES_Paper_Cardboard	Paper, cardboard	8.37
RES_Biogas	Common sludges, MSW landfill, total manure, animal waste	4.68

The data are based on a report on availability of biomass in 2008, and projections for 2010, 2020 and 2030 [86]. From these datapoints, linear interpolation between two subsequently available years and extrapolations were carried out to create a data series from 2015 to 2050 with a 5-years interval.

In order to avoid not to compete with other possible uses, only biomass residues are considered, with the exception of roundwood. The higher price of roundwood is an indication of other competing applications to this raw material. Also, paper & cardboard is a category that needs to be treated carefully, because although despite being a residue, from a circular economy and sustainability perspective, it should, when possible, preferably be sent to recycling and material recovery.

Prices of resources are assumed the same across Europe. No energy crops are included in order not to compete with food production. Figure 3-7 shows the assumed evolution of biomass availability in Norway over the modelling timeframe.

Residues and wood are the largest biomass resources, together making up 84% of the total biomass available. While biomass availability increases from 2015 to 2020, it is assumed to decrease after 2020 (the availability of each biomass resource decreases by 25% from 2020 to 2025). For other Nordic countries, biomass availability is assumed to decrease even more (e.g., approximately 50% decrease in Sweden and Finland). While the overall biomass availability (i.e., sum of all considered biomass types listed in Table 3-11) is based on the numbers from the atlas on biomass potentials, fixed shares have been used to subdivide the overall availability into the different categories. These ratios are the same for all the Scandinavian countries and they are 3%, 28%, 56%, 4%, 8% and 1%, respectively for the categories as listed in Table 3-11.

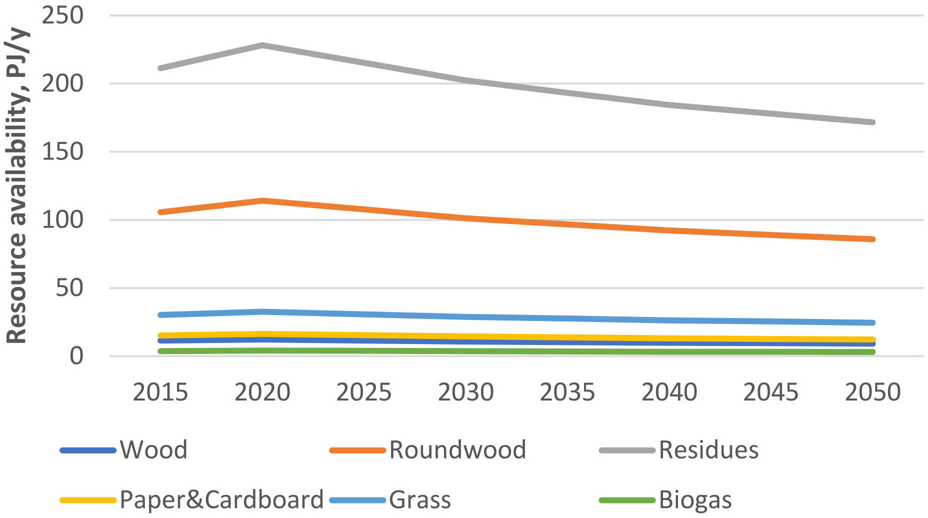


Figure 3-7: Original data from the openENTRANCE dataset for biomass availability in Norway

In a recent master thesis work, the data for Norway have been disaggregated into 5 regions [87]. The disaggregation of the biomass resource potential was made based on the surface area of the considered regions, which hence results in the same shares for all different biomass categories.

Based on this analysis, we have identified some weaknesses and possibilities for improvement of the dataset:

- The dataset is based on projections and extrapolation from relatively old data (2008). These data could be updated with more recent statistics (e.g., from 2020).
- Subdivision of the total available biomass in the different categories was based not on the actual data available on the subcategories but on a predefined ratio between the different biomass types. This ratio was the same for all countries in the dataset, and hence rather resembles a European average than the real situation in the North. Instead, ratios based on the biomass availability specific to the different countries could be used. In reality, great differences between biomass resources in the different countries exist. The Nordic countries are characterised by low population densities, which is typically related to relatively lower municipal solid waste (MSW), while at the same time, the potential of resources such as forestry biomass is higher here as compared to many countries in continental Europe. Subdivision in the different biomass categories could be done based on actual data on biomass availability for the different countries.
- Disaggregation for the 5 Norwegian regions was carried out based on surface area of the considered regions. However, biomass potential is not uniformly distributed in space. Biomass such as MSW and sludge largely depend on population. Due to climate, woody

biomass is more available in the south of Norway, rather than the north. Industrial residues depend on location of the industries. The disaggregation for the regions could be improved by following more appropriate principles than considerations of the surface area.

- Biomass prices were assumed the same for all the considered countries. Costs could be differentiated to better represent biomass prices in the different geographic regions.
- Biomass availability was projected to decrease from 2020 to 2030. If a shift towards a more circular economy will take place in the next years, it is reasonable to assume that biomasses such as MSW and paper&cardboard will decrease in the future. However, for the Nordic countries there is no specific reasons why other biomasses such as residues from forestry and agriculture or woody biomass should decrease in future years. For the Nordic countries, with large forestry biomass resources, which are currently underexploited, projections on the evolution of biomass potential could be discussed and different scenarios considered.

The list suggests an almost completely new dataset for biomass availability and prices. To build a new dataset is a considerable amount of work. To start working through this list of improvement suggestions, we used sector specific models such as SiTree to provide alternative scenarios for available resources from harvest residues from forestry. These scenarios can be used to improve the datasets on available wood residues that are currently used in the GENeSYS-MOD model. Sector specific models can also be used to determine costs specific to individual countries and/or regions. Resources that were considered here as harvest residues or GROT were branches & tops and unmarketable stem sections. SiTree output from the reference scenario, BAU, was used to estimate the available resources from harvest residues from the forest sector. In order to estimate the potential of harvest residues for bioenergy, we used cost functions for residue harvesting [88] and developed cost-supply curves for individual 5-year periods for each Nord Pool region (Table 3-12). Cost-supply relationships for harvest residues were represented as plots of extraction costs (€/ton) versus cumulative supply (tonnes). The total supply of harvesting residues was estimated using the species-specific tree allometric equations developed by Smith et al. (2016, 2014), Marklund (1988), and Petersson and Ståhl (2006) [43]. Cost of residue extraction from plot to roadside were estimated at the plot level according to Rørstad et al. (2010) [88] and Berseng et al.(2013) [89], combining loading, transport and unloading costs. While foliage is not included in the biomass potential (it is assumed to drop off at landing), it is included to estimate extraction costs since it is assumed that residues are forwarded just after timber harvest. To be included in GENeSYS-MOD, extractions costs and biomass supply were converted into M€/PJ and PJ, respectively, according to specific calorific values for each tree part (branches, unmarketable stem sections and foliage) and tree species (spruce, pine and birch) [90].

Table 3-12: Nord Pool Regions for Norway

Nord Pool region - Norway	County-Norway
NO1	Innlandet + Viken
NO2	Vestfold og Telemark + Agder + Rogaland
NO3	Møre og Romsdal + Trøndelag
NO4	Nordland + Troms og Finnmark
NO5	Vestland

The potential supply of harvest residues is stable over time in the coming years with an accumulated 5-year supply of approximately 63.5 PJ (12.7 PJ/year) and 63.1 PJ (12.6 PJ/year) for the period 2023-2027 and 2028-2032, respectively, at a cost of 2 €/GJ (Figure 3-8). When looking at the whole simulation period (2023-2102), the potential supply of harvest residues is relatively stable over time with the lowest 5-year supply of 54 PJ (10.8 PJ/year) for the period 2032-2037 and the highest 5-year supply of 91.2 PJ (18.2 PJ/year) for the period 2098-2102, at a cost of 2 €/GJ.

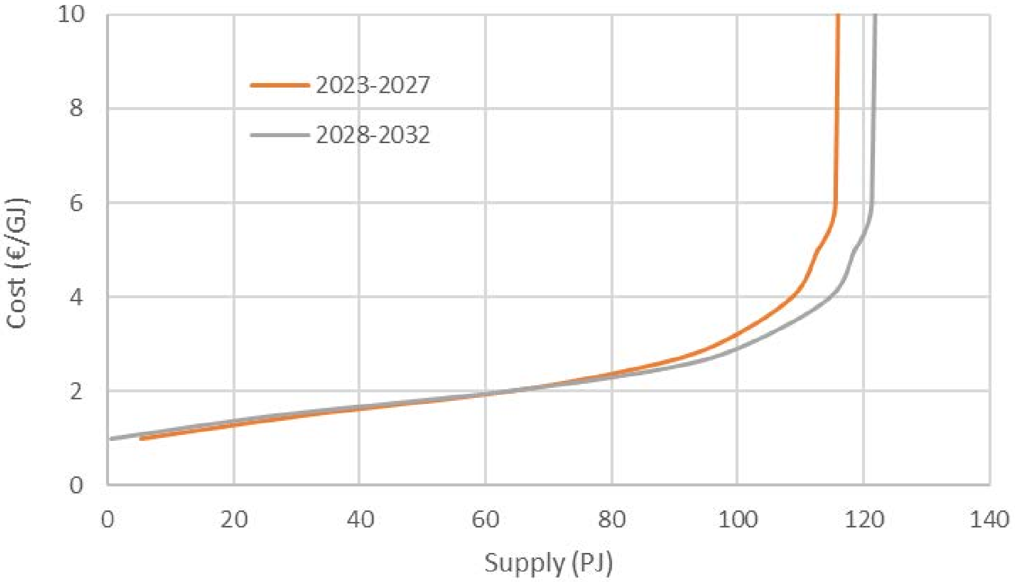


Figure 3-8: Cost-supply curves for harvest residues in Norwegian forests for two periods until 2032 at the national level. Periods after 2032 are left out to improve readability and highlight the importance of year 2030 for climate targets. Plots with costs > 10 €/ GJ are left out to improve readability.

At the regional level, cost-supply curves showed a general trend where region NO1, where most of the productive forests are located, has the largest supply of harvest residues (Figure 3-9). For example, for a cost of 2 €/GJ the NO1 region indicates a supply of approximately 50 PJ for the period 2023-2027, equivalent to 10 PJ/year.

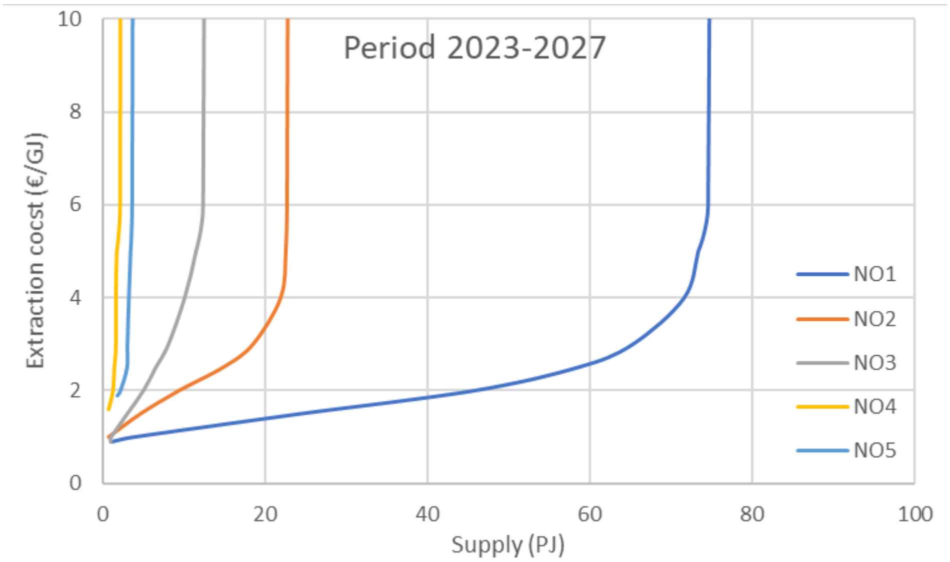


Figure 3-9: Cost-supply curves for harvest residues in Norwegian forests for the period 2023-2027 at the regional level. Plots with costs > 10 €/GJ are left out to improve readability.

To address the next research question "*How do different assumptions on bioenergy in an energy system model (e.g. current and future bioenergy potential) affect the results of the analysis?*", we have chosen to investigate the impact of updating the dataset for biomass availability.

To assess how this parameter affects the results we have considered three different cases:

1) The reference case, where the dataset is the original, openly available openENTRANCE techno friendly scenario dataset,
2) While keeping the other parameters unchanged, biomass potentials for the Scandinavian countries were considered stable over the years and equal to those of the benchmarking year 2015,
3) While keeping the other parameters equal to case 2, GROT was added as additional Residues available in Norway. GROT availability was obtained through SiTree by considering the prices for residues used in the model (see Table 3-11).

Table 3-13 shows a summary of the results obtained (we only analysed data/results for Norway).

Results for the installed capacity of power production from biomass are not affected by the change in biomass resource availability. Table 3-12 shows that installed capacities decrease from 0.55GW installed capacity in 2015 (1.6% of all installed power generation) to 0.025 GW installed capacity in 2050. The same is true for the installed capacities for use of biomass in both industry and the building sector.

Table 3-13: Summary of the results for Norway from 3 different cases, with different biomass availability

			2015	2020	2030	2040	2050
all cases GW	Installed power production capacity	Biomass	0.55	0.41	0.23	0.025	0.025
		Rest	33.4	32.1	45.8	49.2	51.1
	Installed capacity, residential heating	Biomass	0.71	0.64	0.41	0.30	0.24
	Installed capacity, industrial heating	Biomass	0.16	0.14	0.19	0.22	0.20
Case 1	Export in PJ	Biomass	342	243	222	184	136
		Biofuel	0	0	0	25,5	21,7
		Biogas	0	0	0	4,37	60,1
	Heat production (industry, res.)	Biogas/mass	21,5	21,5	15,6	11,3	8,13
Case 3	Export in PJ	Biomass	364	248	256	237	165
		Biofuel	0	0	0	28	20
		Biogas	0	0	0	5,79	66,6
	Heat production (industry, res.)	Biogas/mass	21,5	21,5	15,6	11,3	8,13

In all three cases, all available biomass resources in the benchmarking year 2015 are used with just above 90% being exported outside Norway and about 5 % used by residential buildings for heating purposes. In the subsequent years, all available grass, paper & cardboard, wood and residues are entirely used, while roundwood is not used for energy purposes anymore (the model does not find it cost efficient). Until 2040, over 90% of the Norwegian used biomass is exported. From 2040 onwards, this declines to just above 80%, with between 6-10% of all used biomass being turned into biofuels for use in the transport sector (exported). All three investigated cases show the same behaviour, suggesting that although the model does not find a cost-efficient use for the available biomass within Norway, Norwegian biomass is an important cost-efficient tool for the decarbonisation of the energy systems in e.g., Scandinavia and/or Europe.

The fact that all available biomass is used in all three considered cases (except for roundwood, which is considerably more expensive of the other resources) indicates that there is potentially a need for more biomass with a price lower than 8 M€/PJ.

Our last research question was *"How will the evolution of bioenergy influence the LULUCF sectors and how can sector specific models be used to interpret and extrapolate the results of global energy system analysis on future scenarios for bioenergy utilisation?"* The comparison of the three cases for biomass availability indicated that bioenergy might play an important role in the future decarbonisation of the Nordic energy systems. Since only low-price biomass was found accost-competitive resource, only biomass residues from other production processes were used at energy purposes in our analysis. Thus, according to this analysis, the evolution of bioenergy will not have a significant impact on the LULUCF sectors. Many biomass residues have a short life cycle, and they quickly return their carbon content to the atmosphere following natural decomposition. Their use at energy purposes does therefore not impact considerably related GHG emissions. GROT was considered as an additional biomass resource. GROT is a residue of forest harvest, which is currently left in the forests for natural decomposition. While part of the GROT breaks down and returns to the atmosphere resulting in CO_2 emissions, some of it remains in the soil as dead organic matter resulting in an increase in soil carbon stocks. In the case GROT is used for bioenergy, this would result in an increase in CO2 emissions from the LULUCF sector (reduced net uptake in the soil) and reduced emissions in the energy sector [91]. Over the initial period, removal of forest harvest residue reduced the simulated CO_2 sink capacity of forest soils by 0.43 Tg CO_2 year^{-1} (Figure 3-10). The decline in forest soils sink capacity generally decreased over time (Figure 3-10) and the forest soil CO_2 stock was predicted to decrease by a total og 15 TG CO_2 over the simulated period. This reduction in carbon storage in the soil pool may depend on several factors, such as climate, with carbon losses appearing to be smaller under cold climate [92]. Sector specific tools, such as SiTree [89] , can be used to simulate how forestry emissions and carbon balance change as a consequence of increase exploitation of forest resources, such as GROT.

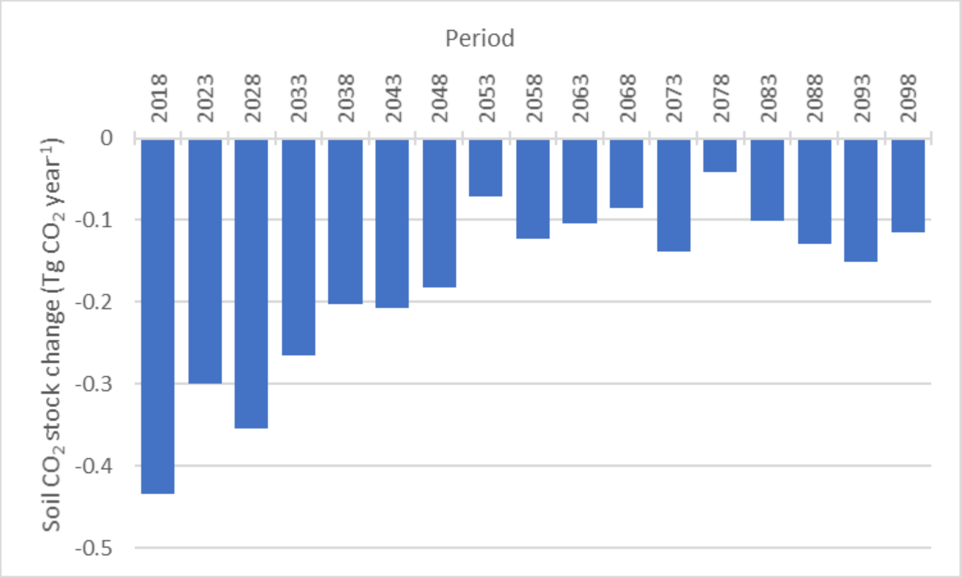


Figure 3-10: Differences in forecasted annual soil CO_2 stock change for the BAU scenario if harvest residues are left in the forest (nowadays) or they are extracted for bioenergy. Differences are expressed as: (BAU with harvest residues left) – (BAU with harvest residues extracted for bioenergy). Values are per year for each 5-year period, i.e., 2018-2022, 2023-2027 and so on.

3.5. Danish Energy Agency

IntERACT linkages to AFOLU greenhouse gas

In the recent Danish Climate Programme [93], the IntERACT model was used to illustrate different pathways for meeting Danish climate targets in 2030 and 2050. The overall purpose of the scenarios was to facilitate a further discussion by showing four different scenarios for meeting the Danish target of 70 % GHG reduction in 2030 (compared to 1990) and climate neutrality target in 2050.

The version of IntERACT used for the Danish Climate Programme included all emissions relevant from a national climate perspective. Within IntERACT, greenhouse gas emissions associated with energy supply and demand were modelled at a detailed level. In comparison, greenhouse gas emissions from AFOLU were exogenous in IntERACT, based on expert judgement. Projected emissions from agriculture, soils and forestry, estimated separately as approximate reductions caused by adopted mitigation measures (published 4 October 2021 in the plan for the green transition of Danish agriculture by the Danish government [94]).

By setting emissions from AFOLU as an exogenous input, IntERACT was able to account for AFOLU emission when determining the level of CO2-emission reduction needed in other sectors to meet the overall CO2-emission target. Further work could investigate a better representation of the AFOLU greenhouse gas emission.

There is a substantial methodological difference in the way GHG emission from the AFOLU sectors is modelled in IntERACT compared to the national GHG inventories. In policy development, there is a need to link expected effects of mitigation measures on the GHG emissions to the baseline emissions scenario, i.e. the national GHG projections, in the Danish case the Climate status and projection [95]. In doing so, it is important to be aware of the methodological difference in how GHG emission reductions are estimated.

BioRES linking AFOLU and energy systems

The BioRES model is a tool that provides a balance of the biomass use in Denmark by simplistic assumptions of the most significant flows. It is transparent and for that reason, a valuable tool in understanding main cause-and-effect consequences. The model calculates the biomass balance, and the model illustrates how much biomass import is needed to ensure balance between biomass potential and biomass demand. For example, increasing the demand for straw (e.g. for pyrolysis), the model highlights if, in turn, create a need for straw import.

BioRES has a great potential for making explorative scenarios evaluating the biomass availability and potential for usage in different energy-generating processes. Typical relevant questions the model could answer are as follows:

- How does changes in land use, e.g. making agriculture more extensive by restoring cultivated organic soils to wetlands or expansive afforestation, influence the biomass potential, in terms of straw production, that can be used for biogas production, pyrolysis or central heating? Furthermore, how does this affect the demand for imported biomass in the form of wood chips or straw?
- How does changes in the livestock population affect the total biogas production?

It was not within this project's scope for the DEA to develop such explorative scenarios. However, it would be very relevant to do as part of future work. Suppose it is a national goal to reduce the reliance on imported biomass. In that case, the model will indicate whether this is likely to happen for a given set of modelling assumptions. Moreover, the biomass flows calculated by the BioRES model can be used directly as input to IntERACT.

As mentioned, BioRES also includes a submodule for estimated GHG emission. The results, however, must be interpreted with large degree of caution and as a rough approximation of the GHG-effect. This is especially true when it comes to comparing the GHG-estimates from BioRES to the national GHG inventory estimates, both historically and for the future. This is due to the discrepancies between the simple modelling approach used in BioRES compared to detailed and comprehensive IPCC emission accounting methodology for the AFOLU sector.

Methods to model GHG emissions from AFOLU linkage to energy system

According to IPCC guidelines for national GHG inventories, emissions in the agricultural sector are estimated separated for the following six categories 1) enteric fermentation of livestock, 2) manure management, 3) rice cultivation, 4) nitrogen flows on agricultural soils (excl. soil organic carbon changes), 5) residue burning, 6) liming and other carbon-containing fertilisers. The LULUCF is consist of carbon stock changes in three carbon pools (living biomass, dead biomass, soils) on 5 land-use classes (forest land, cropland, grassland, wetlands, settlements, and other land), and non-CO_2 emissions caused by changes in the soil C and N dynamics. Neither IntERACT nor BioRES are linking to the AFOLU emissions on the level of detail at this moment and it may be question if this level of detail is even necessary. An important aspect of modelling work is the well-defined purpose of the model. In the context of IntERACT and BioRES, the current objective is to provide explorative scenarios for understanding the consequences of different pathways, which is useful in policy development work. In national GHG inventories the objective is to provide an accurate status by estimates of emissions from the current situation or a frozen policy or business as usual scenario. Currently, the field of agricultural climate policy is in transition, challenging the definition of a baseline scenario and more so how to model and estimate effects of mitigation measures. This condition emphasises the need to select the appropriate model depending on the questions that need answered.

In summary, when considering the level of detail necessary in linking GHG emissions from AFOLU to energy system model, the following modelling objectives are considered crucial:

1. Explore different pathways for meeting climate and energy policy targets across different sectors for a wide range of output (such GHG emissions, energy consumption and costs).
2. Provide a complete emissions inventory.
3. Analyse the effect of specific mitigation measures on GHG-emissions.

4. Needs for more joint research and investigation

4.1. Focus areas

The ideas and topics described in this section result to a large degree from discussions and considerations made within the programme and are based on an enhanced mutual understanding of ongoing work on corresponding energy system models for the Nordic area. The focus is thus naturally on those methods that are involved in WP1 work, and promise collaboration between corresponding research partners. Our goal has not been to make a gap analysis for energy system models and domain-specific models with respect to bioenergy, encompassing all methods and corresponding research institutes in the Nordic area.

4.2. Improvement of the datasets

The dataset is a very important part of an energy system analysis. The development of a database that is representative of the considered countries' real characteristics is fundamental. In order to use large scale energy system models to explore what the role of bioenergy in future energy systems could be, a detailed description of biomass potential and its associated costs is required. The revision work and analysis carried out in this project revealed that the current openENTRANCE dataset for biomass availability and prices (used by GENeSYS-MOD) has significant room for improvement to better represent the actual potential of biomass, especially in the Nordic countries. Some suggestions to improve the dataset are:

- The dataset relies on projections and extrapolation from relatively old data (2008). These data could be updated with more recent statistics.
- Subdivision in the different biomass categories could be done based on actual data on biomass availability for the different countries.
- The disaggregation in regions within a country could be improved by following other principles than considerations on the area of the different regions. Sector specific models and regional statistics can also provide a more accurate description of biomass availability.
- Biomass prices could be updated to better differentiate them according to the different geographic regions.
- Projections on the evolution of biomass potential could be discussed and different scenarios considered.

An update and detailed dataset would require the access to detailed statistics, high quality resource potential studies and expertise from different sectors. However, the information collected could be used to create a common dataset that could be adapted to be used by the different energy system models. The project has shown the potential for different sectorial models to feed data into and support multi-sector energy modelling, analysing the energy transition. In a Norwegian context, results from this report and SINTEF-NIBIO collaboration have shown that sector-specific tools, such as SiTree for the forest (LULUCF) sector, can contribute to provide more accurate and realistic estimations of biomass available from harvest, which can be used as input data into an energy system model. While this tool was only used for Norway, SiTree could be developed to improve estimations on forest biomass availability for different Nordic countries, provided that the countries have access to the necessary data (at the tree and stand level) and specific functions (i.e., growth, mortality, etc.). Apart from SiTree, other specific simulation tools for the forest sector, such as Heureka [96]. or GAYA [89], might be of interest to the Nordic region.

This project has revealed the need for open, accessible, and well documented datasets that the different existing modelling frameworks can build on. To be able to study the energy transition that lies ahead of us, to deliver policy-relevant and fact-based insights that have value for decision makers as well as scientists and modellers, advancing the research frontier and capturing challenges and characteristics specific to the Nordic context, a suite of different models and experts from different disciplines working together is a necessity.

4.3. Other proposals

a) Finding a method to disaggregate the total potential of biomass to potential of each type of biomass for further integration and development of the ON-TIMES model

b) Developing a method to include emissions from biomass in the model by making some changes in the LULUCF representation in the ON-TIMES model (to avoid double counting).

c) Further investigating the missing link between the use of bioenergy and the demand of energy resources relating to the production of biomass, and the emissions associated with it, through a life cycle perspective.

d) Integrating other environmental impacts in the TIMES model and using planetary boundaries framework as a benchmark for measuring the sustainability of biomass.

e) Investigating how LCA methods can be used in energy system models, without introducing errors when mixing methodologies. Case in point: The national inventory reporting following the UNFCCC guidelines does not allow the use of LCA-methods.

f) Expanding BioRES to all Nordic countries. This would make it possible to develop Nordic biomass scenarios for usage in energy system models like ON-TIMES and GENeSYS-MOD.

g) Identified topics related to the BeWhere model

- Actual energy and materials flows, emissions from the farmland/agriculture sector
- Size and location of existing biogas plants in the Nordics
- Historic and future energy demand in the local region – trade of biomass feedstock and biogas across the country.
- Factors affecting the conversion efficiencies of co-digestion, also CAPEX and OPEX.
- Existing infrastructure (natural gas grid, power grid, gas stations)
- Water and biodiversity loss due to crop production – also, direct and indirect emissions (LCA methodology – uncertainty analysis)
- Impact of climate on crop and livestock production, including future crop demand and dietary change patterns
- Integration with forest biomass residues
- The use of available residues for other purposes such as hydrogen production and value-added bio-products.

5. Inputs to the update of National Energy and Climate Plans (NECPs)

5.1. Background

About NECPs

The following discussion is based on information provided at the corresponding websites for the Commission [97], where submitted NECPs till the EU can be downloaded, and the Florence School of Regulation [98].

NECPs are part of the EU's work to ensure the fulfilment of the Energy Union and the achievement of the 2030, as well as long-term objectives and targets of the Energy Union in line with the Paris Agreement. In existing EU regulation, there are binding targets specified for the union as a whole, with respect to cuts in greenhouse gas emissions, share of renewable energy in final energy consumption, energy efficiency, and electricity interconnections. Specific goals are also stated for 2030. The NECPs for 2021 – 2030 show how each Member State does its part to for the Union to jointly reach those targets, by describing the national targets and measures for energy and climate policies that are expected to be implemented in the 10-year period to achieve those targets.

Unlike what was the case for the EU 2020 targets, the national 2030 targets and measures described in NECPs are non-binding, except for the non-ETS greenhouse gas emission target. However, the commission may identify a need for additional efforts by Member States, as well as EU policy and measures after having assessed the NECPs.

NECPs for 2020-2031 shall be updated by 30 June 2023 (draft) and 30 June 2024 (final). This is to account for significant changing circumstances, during the 10-year period, and reflects the need for stocktaking, since the NECP’s were submitted to the EU by the end of 2019 and both EU targets and many national policies may have been amended since then.

WP1-inputs to NECPs

One aim of the Nordic Energy Outlook programme is to discuss if and how the results from the programme can be used for following up on the integrated national energy and climate plans (in 2023 and 2024), and if the results can provide a regional perspective – notably a Nordic perspective - to the updated integrated national energy and climate plans submitted by the Nordic countries. We are focusing on the Nordic countries represented in WP1, i.e. Denmark, Sweden, and Norway.

Most of the work carried out in WP1 is described in the project outcomes in Section 0. Since those research questions focused mostly on improving methods and datasets, and not on carrying out new analysis focusing on NECPs, the outcomes can in few instances be utilised directly. Hence, the comments we provide to the NECPs are developed on the basis of the expertise of involved researchers in the field of bioenergy and the Nordic energy system, and not only the work in WP1.

5.2. Comments to the Danish NECP by DEA

From an energy system perspective, the NECPs are an important tool, as they require member states to take a holistic approach to climate and energy policy. They are focusing not only on GHG emission reduction but also on renewable energy, energy efficiency, security of supply, markets, infrastructure, and research and competitiveness.

The Danish Government has set an ambitious national target of reducing greenhouse gas emissions by 70 % in 2030 compared to 1990 levels. Denmark has set an ambitious course towards at least 55 % renewables energy in gross final consumption in 2030. Presently, bioenergy makes out a large share of the country's renewable energy.

The energy production from biomass has more than doubled since 1990 - primarily due to the policy agreement of 1993 (the Biomass Agreement: requires power plants to use 1.4 million tonnes of straw and wood, equivalent to almost 20 PJ per year) and the policy agreement of February 2008 on the increased use of straw and chips at the large cogeneration plants (up to 700,000 tonnes in 2011). The conversion from fossil fuels (primarily coal) to biomass at the large, combined heat and power plants expanded after the Energy Agreement in 2012 due to improved incentives.

At the same time, biomass consumption continues to rise as a source of energy for the supply of heat in district-heating plants and smaller installations for households, enterprises, and institutions.

Denmark supports the updated Bioeconomy Strategy launched by the European Commission in 2018. Moreover, the Danish Government established a National Bioeconomy Panel, which provides advice to the Government on sustainable utilisation of biomass resources to fodder, food products, materials, and energy purposes. A voluntary industry agreement exists in Denmark to ensure that biomass used in Denmark fulfils internationally recognised sustainability demands. Thus, the biomass must come from forests that are operated sustainably, and the use of biomass must lead to real CO2 reductions. The sustainability of the used biomass must be documented in annual reports verified by a third party.

From a regional Nordic perspective, the large difference in biomass potential (e.g., forested areas) and the use of biomass for energy purposes across Nordic countries is worth noting. Perhaps an independent point of future Nordic collaboration could be to understand these differences further and consider the potential for better integration of the Nordic bioenergy markets. For example, in the context of NECP, one could examine the role biomass could play for the security of supply in a Nordic context.

5.3. Comments to the Norwegian NECP by SINTEF and NIBIO

The Ministry of Climate and Environment (Klima- og miljødepartementet) informs [99], Appendix A.4, that Norway is not obligated to submit NECP to the EU. However, in 2019 the Government made a plan [100] that shows how Norway shall comply with obligations in regulations for non-ETS sectors and LULUC, which was submitted on a voluntary basis. In the following we have made comment to that plan. It states:

"The Government will introduce new measures designed to maintain or increase the carbon stock in forests and facilitate greater use of biomass as a substitute for fossil energy sources and fossil-intensive building materials, thus ensuring that forests can continue to play their crucial role in the context of climate change."

This is the only place bioenergy for heat (or electricity), in industry and in commercial and residential buildings can be anticipated to be mentioned, however stressing the use of biomass as a substitute for fossil energy sources. Biofuels for the transport sector to substitute fossil transport fuels are frequently mentioned. Waste-to-energy (WtE) from MSW is mentioned, and the possibility for CCS connected to WtE plants.

The main recommendation from NEO WP1 for Norway is that biomass for stationary bioenergy, especially for heating purposes, should be better represented. This is also the case for national energy system simulation tools and connected national economic models, where a CO_2 reduction target is typically set, and reached by optimising the energy system economics. The following is suggested regarding how the results from the programme can be used:

1) Biomass for stationary bioenergy, especially for heating purposes, should be better presented, and as well included in the models and simulations that lies behind the NECP, if this is not sufficiently included today.
2) There should be a focus on the substitution effect of biomass resources not only for substituting fossil fuels, but also for substituting hydropower electricity that could rather help reduce CO_2 emissions in other sectors instead of the extensive use of direct electric heating that we have in Norway today. This would also relieve the pressure on the electricity grid and the private consumers feeling the economic effect of expensive electricity. This electricity might also be partly imported as well as partly be of non-renewable origin.
3) BECCS (Bioenergy CCS) should be presented as one future option, giving net negative CO_2 emission reductions.
4) Biomass export/import should be considered, as transport of biomass between countries happens to a large extent already today. In general, the Nordic perspective is lacking and should be more highlighted, as energy stored in biomass and MSW and as electricity flows easily across borders.

Furthermore, we have the following suggestions for how national energy system models should be improved to provide better and more precise results to be utilised for NECP:

1) The presentation of the biomass resources available for energy production (including their geographic distribution) or alternative uses should be completed and more detailed. This includes both forest and agriculturally based biomass, as well as all relevant biogenic waste streams.
2) The presentation of the bioenergy technologies should be expanded to all the technologies significantly contributing to the Norwegian energy system today, e.g. space heating with wood stoves, as well as those which could become significant contributors in the future.
3) Alternative non-energy uses of biomass should be included in detail, including their CO_2 savings potential (amount and timeframe) as well as connected costs. The circular society will be of importance here, as it will impact especially the WtE sector when it comes to energy production but also other energy intensive industries, e.g. metal production, where today fossil reductants and materials are used to a great extent, but where biobased alternatives (e.g. biocarbon) are available and wanted.
4) Enhanced energy system models with more comprehensive and correct representation of biomass resources and biomass conversion technologies and their connected economics, could provide better advice on how to best reach Norway's CO_2 reduction targets. At the same time, all significant alternative uses of the biomass should be included to enable a realistic optimisation of the complete system.

5) Biomass export/import should be better described.

It is fundamental to understand the implications of an increased use of biomass for energy purposes. Land use, land-use change, and forestry (LULUCF) have a fundamental impact on the carbon balance in the atmosphere. At the same time biodiversity must be conserved. An increased use of biomass for bioenergy might have an influence on LULUCF, and further energy system analyses with detailed enough national energy system models are needed to provide recommendations for the future biomass use to reduce CO_2 emissions both in the short and the long-term. The time horizon (short vs long-term) is crucial from a forest management (and LULUCF) perspective, since many measures in the sector might not have a significant effect in the very short-term (e.g. 2030 climate targets). For example, it is expected that a small number of measures (e.g. fertilisation, reduce deforestation) will have an impact in the short term. On the other hand, some measures, such as large-scale spruce forest planting, would have a negative impact in the short-term but would result in a positive effect on climate change mitigation after the second half of the century [48]. Therefore, it is important to consider the trade-off between short and long-term effects, as well as the uncertainty associated with models and future projections, which increases with increasing time horizons.

5.4. Comments to the Swedish NECP by IVL and KTH

Comments by IVL

Sweden's NECP [101] states that "The energy policy must therefore create the conditions for effective and sustainable energy use and a cost-effective energy supply in Sweden while minimising the damage to health, the environment and climate and facilitating the transition to a sustainable society" (The Ministry of Infrastructure of Sweden, 2020). Many of the Swedish energy policies are in the form of funding systems and information-based schemes. Some examples of these are Klimatkliv, a fund for local investment to reduce GHG emissions. Fossil-free Sweden is another one that helps municipalities, companies, public operators, and civil society identify obstacles and accelerate the reduction in GHG emissions.

The importance of collaboration between Nordic countries is mentioned several times throughout Sweden's integrated NECP. In January of 2019, the prime ministers of the Nordic countries adopted a declaration with a stated goal of making all Nordic countries carbon neutral. The Nordic countries' cooperation, coordination, and dialogue are done through the Nordic Council of Ministers. Within this cooperative framework, knowledge can be shared, and matters of common interest are discussed. An example of this includes establishing a market forum for the Nordic electricity market. The forum's objective is to ensure the optimal allocation of resources and cost-effectiveness while transitioning to a sustainable energy system. The forum includes different types of stakeholders, both political and non-political. On a national level, however, Sweden has no specific goals regarding market integration.

The integrated NECP states that the ON-TIMES model is used to assess the energy supply and analyse climate scenarios in the Nordics based on assumptions about how the cost of different current technologies would develop (The Ministry of Infrastructure of Sweden, 2020). This helps the Nordics in general – and Sweden specifically – to maintain a cost-effective and sustainable energy supply. The improved level of detail in terms of a modified potential, additional biomass sources from agriculture, emissions from biomass feedstock production, and the associated environmental impacts from this project can complement the cost aspect of deciding which technology to support incentives.

The Swedish NECP does not include specific estimations for future biomass potential from agriculture. Today, large amounts of biofuels are imported, and even if there is a recognition of a national potential, there is no government body or state policy that controls the balance between import and domestic production. Updating and integrating further knowledge of the biomass potential from agriculture into ON-TIMES could contribute to a further updated scenario for the future.

The result of this project shows that the production of agricultural biomass requires energy and resources that cause GHG emissions that are not taken into consideration when talking about the climate neutrality of biomass. Since these upstream impacts are not accounted for in the ON-TIMES model, agricultural biomass should not be regarded as truly climate neutral. As bioenergy consumption is projected to increase to 161 TWh by 2030, the accuracy of the levels of emissions from producing agricultural biomass (which are not only GHGs) will become increasingly important. Awareness of this can help relevant actors make better-informed decisions when planning climate strategies.

Another proposition is to focus on strategies to minimise the environmental impact from the use of machinery, fertilisers, and pesticides. This can be accomplished through implementing better agricultural practices. To reduce the loss of soil carbon, abandoned/degraded land can be used for growing energy crops. Furthermore, the use of biomass residue has been shown to have a lower impact than using virgin biomass. There are already regulations that encourage the use of residue to produce biofuels, for example, the renewable energy directive (RED), but further incentivisation may be beneficial.

Comments by KTH

The impacts of climate change in the agricultural and livestock production have to be incorporated in the NECP. A few CLEWs scenarios are proposed in the study, "Towards Sustainability (TS)" and "Stratified Societies (SS)". The choice of conversion technologies and derived energy products (biogas, biomethane, and bioelectricity) is determined by looking into the total systems costs and life cycle emissions.

Sweden's NECP [101] does not propose or discuss any future biogas support scheme (e.g., subsidies, tax rebate) for increased share of biogas in the energy mix. However, Sweden has had an ambitious plan of taxation of fossil fuels being used for heating and transportation since the beginning of the 1990s to increase the share of renewables in those energy sectors.

The Swedish rural development programme was running in 2014 - 2020. It is a part of the EU's Common Agricultural Policy (CAP) and includes support for organic farming, environmental and climate measures, and animal welfare. Measures specifically intended to reduce greenhouse gas emissions are e.g. the product and use of renewable energy (including the production of biogas and the planting of perennial energy crops), conversion from fossil to renewable energy sources, improved manure management, more efficient nitrogen use, climate and energy advice, measures to prevent nitrogen leaks, and other separate climate and energy projects.

The Rural Development Network completes Sweden's Rural Development Programme. The Network brings together local, regional, and central operators to exchange information and experience, with the aim of improving the implementation of its EU-related programme.

Since 2015, there has been a support system for the production of biogas from anaerobic digestion of manure [102]. The support aims to increase the production of biogas from manure, obtaining twice the environmental and climate benefits by reducing methane emissions from manure and replacing fossil energy. Many environmental benefits can be obtained by digesting more manure. It reduces GHG emissions and eutrophication of fresh and marine water and produces biogas which can be used as energy. The biogas obtained can be used to generate electricity or heat and as a fuel for vehicles. The maximum support is SEK 0.40 per kWh of biogas produced. The Rural Development Programme also provided support for investments in new biogas plants.

In 2018, temporary support was introduced for the production of biogas upgraded to vehicle gas (biofuel) which was not produced from sewage sludge or landfill gas. To improve competition in the sector, and in response to the Swedish Government's proposal in the revised budget in autumn 2019, the Swedish Riksdag decided that a total of SEK 100 million in support should also be paid out for this type of biogas production in 2019.

The majority of Swedish biogas is distributed with trucks. Gas pipeline infrastructure is limited to the south-western part of Sweden [103], and can be further explored. Transporting biogas with trucks is worse environmentally and prevents the biogas reaching the northern territories, far from production.

An obligation to reduce petrol and diesel consumption was introduced in Sweden on 1 July 2018 to promote the use of biofuels [104]. All fuel suppliers must therefore reduce the greenhouse gas emissions of petrol and diesel over their entire life cycle by a certain percentage every year, by gradually increasing the amount of added biofuel. The reduction obligation makes an important contribution to phasing out fossil fuels in transport.

The Swedish Government has asked the Swedish Energy Agency to suggest reduction levels for 2021–2030. It has also examined whether the same reduction should apply to petrol and diesel and whether or not high-blend biofuels should be included in the reduction obligation. The report on this task was submitted in June 2019 and it was completed on 25 October 2019. The process for successively increasing the reductions after 2020 is continuing.

Concerning national objectives on energy security, domestic production of biogas can play an important role for the national energy security, as:

- that should increase the flexibility of the national energy system.
- it can improve the resilience of regional energy systems.

Sweden has no national targets for the share of renewable energy in 2030. However, the Swedish Energy Agency’s 2016 reference scenario with conditions recommended by the EU indicated that renewable energy would account for 65% of gross energy consumption in 2030. The Agency's latest long-term scenarios [105] show that this is still a reasonable contribution which should be achievable with the policies adopted.

In this project, it has been shown that 152 PJ of biogas can be produced from crops residues and manure in the Nordic countries. That amount can then be upgraded to 90 PJ of biomethane or converted to 46 PJ of electricity and 76 PJ of heat – if all the biogas were to be used as fuel in CHP plants (see Section 3.3).

In 2019, 382 PJ of non-renewables were used for electricity production in the Nordic countries [82]. This project has shown that the potential biogas production from crops residues and manure in the Nordic countries can cover 11.9% of that electricity consumption, if all that biogas production was used to meet electricity consumption needs.

It has also been shown (see Chapter 3.3) that 11 % of the fossil oil used for refining vehicle fuels can be replaced by biomethane, i.e. upgraded biogas, being produced in the Nordic countries.

Thus, an increased production of biogas in the Nordic countries can also contribute to the long-term emissions targets for GHG emissions.

6. Conclusions

6.1. Summary

a) Bio-resources in Nordic countries, except forest sector (ON-TIMES inputs)

In this study, we have estimated the bio potential for Nordic countries, excluding resources from the forest sector. There is a large span in the estimated bio potential for Sweden, ranging from approximately 1,2 to 40 TWh/yr. The current potential is greatest in Sweden, but Denmark's future potential is predicted to increase. In Norway, the potential is limited due to delimited agricultural land areas. The main biomass source is straw from cereal production, followed by manure, legumes, energy crops and grazing grounds. The agricultural potential is influenced by the competing land use, mainly from the food sector, and changing diets influenced by climate change. Other barriers are limited infrastructure, policy tools and pricing. Further disaggregation of the estimated biomass potential from agriculture is needed to feed it into the energy system model ON-TIMES.

b) Biomass availability and prices in the openENTRANCE database (GeneSys-Mod inputs)

There is a large potential to improve the openENTRANCE database with regard to biomass availability and prices, especially in the representation of the Nordic countries. The dataset is a very important part of an energy system analysis. This project has revealed the need for open, accessible, and well documented datasets that the different existing modelling frameworks can built on.

c) Biomass from the forest sector (GeneSys-Mod outputs)

Biomass is an important cost-efficient tool for the decarbonisation of the energy systems in Scandinavia and Europe. The fact that all considered available biomass residues are used in the analysis indicates that there is potentially a need for additional low-price biomass (i.e., biomass residues). Since the availability of harvest residues from the forest sector is closely linked to harvest levels, increasing harvest levels would result in larger biomass supply that could be utilised for bioenergy. Another possible solution to get more biomass for energy production could be increasing the use of roundwood for energy purposes at the expense of pulpwood.

d) Biogas production (BeWhere model and outputs)

In the Nordic countries, there are huge amounts of agricultural residues and manure for biogas production. The biogas potential is estimated to 152 PJ in 2020, which is around 6 times the current production. Utilising this potential to the fullest would allow for around 48% of natural gas consumption to be replaced by biomethane. Biogas could also replace 11% of fossil oil (diesel), thereby contributing to a reduction in GHG emissions of 55 million tonnes.. We need to consider the lifecycle emissions in the supply chains of biogas production, including emissions from livestock and crop production. The utilisation of bio-fertiliser not only substitutes the synthetic fertilisers and generates revenues, but also contributes to reducing GHG emissions. An increased production of biogas in the Nordic countries can also contribute to the long-term emissions reduction targets for GHG emissions. Hence, the role of biogas sector should be appropriately reflected in the Nordic countries' national energy and climate plans (NECPs).

The proposed geospatial modelling framework would determine the optimal location, size, and type of the technologies based on the feedstock supply, energy demand, costs, and prices, as well as policy instruments such as subsides and carbon tax. All revenues streams and emissions need to be accounted and considered as input data for the model. The study proposes a spatially explicit optimisation model for evaluating the choice of technological options (CHP for bioelectricity and/or biomethane upgrading for transport fuel).

The water-energy-food (WEF) nexus is central to sustainable development. The agricultural sector requires fresh water for crop production and energy for cultivation and transport of food commodities. The impact of climate change on crop production; the use of fertiliser, energy and water; and agricultural practices needs to be considered in the integrated model. Our work proposes further research in developing the inextricable linkages between these critical domains, which requires an integrated approach to ensure water and food security, sustainable agriculture, and energy production in the region. The impact of climate change in crop production should also be determined. In this regard, we propose two FAO scenarios, i.e. "Towards Sustainability (TS)" and "Stratified Societies (SS)", for both livestock and crops, considering all the Nordic countries. The TS scenario represents the best-case scenario, with minor temperature changes and the lowest CO_2eq concentrations whereas the SS is the worst-case scenario with the higher temperature changes and CO_2eq concentrations.

Finally, the project provides a sound basis for integrating CLEWs aspects into the BeWhere techno-economic optimisation model. The CLEWs framework assists the exploration of interactions between (and within) CLEW systems via quantitative means. As the model does not optimise the benefits at the plant levels - thus, welfare aspects such as security of supply, prices, and environmental costs are of great importance in the modelling of bioenergy systems. Its multi-institutional application to the case of Nordics would help in promoting the security of the food, energy, and water systems.

e) Links to land-use and agriculture (IntERACT and BioRES models)

There are several ways to integrate the AFOLU sector into energy system models. In the work package, the links to agriculture, forestry and land-use were made on different levels of detail. Depending on the objective of the modelling, agriculture and LULUCF emissions can be added simplistically as exogenous output for the sector as a whole or, in the case of IntERACT, on a slightly more aggregated level for agriculture, soils, and forestry separately. In the BioRES model, we found a more detailed link to AFOLU, where livestock, crop and soil types were specified.

f) LCA factors may lead to double-accounting in energy system models (ON-TIMES inputs)

The aggregated results from LCA studies cannot be implemented directly to the TIMES model. Furthermore, the LCA also includes the emissions from SOC change. Including this information would cause a double-counting problem as the impact from the LULUCF sector is already modelled at an aggregated level in the TIMES model. The fact that energy use in the agricultural sector is already included in the model also made it more difficult to integration the LCA results. Hence, integration of the life cycle thinking throughout the supply chain of bioenergy and the existing data used in the TIMES model needs to be further investigated. More LCA study targeted on agricultural biomass in the Nordic countries will be useful. Lastly, there is also a need for a harmonisation among LCA frameworks to reduce the variation in the environmental impact results.

g) Emission estimates between models (IntERACT and BioRES vs. sector-specific models)

Despite the issue of methodological discrepancies, models such as IntERACT and BioRES are pivotal tools for providing policy insights into the interactions across different sectors. Insights that typically cannot be provided by dedicated sector-specific models, such as those commonly applied in LULUCF emissions inventory. Whereas sector-specific models are needed to provide a precise inventory modelling framework that complies with UNFCCC guidelines, it is often necessary to align modelled emission estimates with the national GHG emissions inventories. However, doing so is often very difficult due to methodological discrepancies. Because of this, models dealing with the AFOLU sector often risk producing results that are not directly comparable to official national inventory reporting – as the models in question do not conform with the IPPC guidelines for national GHG emission inventory. This can be due for example to differences in stratification of input data, choice of method tier level and the segregated number of sources/sinks in the AFOLU sector.

6.2. Takeaway

The takeaway from the study fall into two broad categories: bioenergy potentials and environmental impact assessment for bioenergy.

a) Bioenergy potentials

The biomass residue potential for energy use might be larger than that resulting from some of the studies and should be further investigated. Ensuring research progress and improving energy system models requires developing open, accessible, and well documented datasets. Joint efforts and collaborations between institutions with expertise in different energy-related sectors is key. There is also a need for a further disaggregated level, specific to crops. However, caution should be applied when integrating the AFOLU sector into energy systems models.

b) Environmental impact assessment for bioenergy

As the demand for biomass will increase in the future, more studies targeted on quantifying the environmental impact of the Nordic agricultural biomass sources need to be done. For instance, there are several LCA frameworks, leading to different GHG calculations. Hence, there is a need for harmonisation, and to understand of how such estimates consistently can be applied in energy system models. Other environmental impacts than GHG emissions also need to be investigated and included in energy system models.

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A. Appendix

A.1. IVL review biomass potential

Table A-1: IVL review of biomass potential

Author	year	Institute/ Publisher	Biomass source	Potential	Quantified, total	Key aspects affecting the potential	Comment
Astrup, T., Tonini, D., Hamelin, L., & Wenzel, H.	2011	Aalborg University	Straw, manure, animal fat, rapeseed, willow, grass, industrial waste, meat and bones	The estimated potential did not satisfy the demand in a studies scenario. Energy crops such as willow had to be included.	176-184 PJ		Excluding energy crops
Belhaj, M. et.al.	2010	IVL	salix, rörflen and hemp	Sweden has good potential due to large forest areas, peat and wetlands, also established manufacturers and research. The study examines two scenarios for broader CO2 taxes.	1.5 TWh Sweden/yr	Available agricultural land. Policy tools, EU-directives, price on oil and natural gas, investments, stability, increasing competition and environmental goals	One of the first assumptions is that the oil price should be down to 55 $ by 2020 (today's price is 71 $).
Börjesson, P.	2016	Lund Universitet	Cereals, grazing ground, oilseeds, potatoes, sugar beet, legumes, straw, blast, manure	The overall potential is expected to increase 35-40 TWh/yr until 2050. The lower value will occur if there are larger ecological limitations and competing land use.	Total potential from growing crops in Sweden 74 TWh/yr (53 TWh is harvested and 21 TWh harvest residues as straw). 1.7 TWh manure	Technical, economic and ecological limitations. Particularly dependent on market drivers that will exist in the future, including various instruments in agricultural, energy and climate policy.	Straw- theoretical potential based on land, and technical potential include crop losses based on techniques, weather etc. Biogas - cost situation and the economic condition Competing land use
Börjesson, P.	2021	Lund Universitet	straw, manure, gracing grounds, sly	The increased potential from agriculture is 1/3 of the total potential of biomass (56-79 TWh). The estimations have	14-22 TWh 21-33 TWh	Capacity to transform and produce biomass, technical, economic and climate limitations	Until 2030 and 2050, respectively. Sly is a new category from the previous report.

				decreased by 20 % since 2016 due to estimated reduced potential from energy crops. The potential is relatively low due to technical, economic and climate limitations.			The greatest change to 2050 is the agricultural land used for biofuel instead of food production.
Carlsson, A. et.al.	2014	Naturskydds-föreningen	straw from cereals, legumes and blast, manure, salix, *rör flen*, grazing grounds, rapeseed, sugar beet, hemp	Several actors tend to overestimate the potential. Nevertheless is, there are possibilities for an increase in the national production of biofuels. Food production shall be prioritised for agricultural land	7 TWh in 2020	Net energy, competing land use bioproducts, flexibility, scalability, access to fertilisers, crop cycles, techniques, infrastructure, environmental impacts, economy	
Danish Energy Agency	2020	Danish Energy Agency	Straw, waste	The energy potential will be greater if agricultural land is converted to energy crops or forestry. Denmark could, over time, meet the demand of biomass consumption if more agricultural residues are used.	160-180 PJ		Total energy potential for Denmark, including biodegradable waste but excluding energy crops and blue biomass
Dees, M. et.al.	2017	S2Biom	straw, blast, residues from vineyards, fruit trees, olives, citrus and nut plantations, grasslands	No expectancy in increased yield.	0-10 kton dm/region or 0-0.1 ton dm/ha	Competing with food and feed, urbanisation, and land-use change	
Egnell, G	2008	SLU	cereals, straw, blast, legumes	The potential varies within the country but could increase by growing energy crops and further use of land in fallow. The previous low contribution from agriculture is a result of cost and revenue related reasons that impact profitability.	ca 30 TWh	Available land area, choice of crops, geographical location, market price, taxes, subventions, competition, human attitudes	Earlier studies have shown a variation from 1-59 TWh
Fossilfritt Sverige	2021	Fossilfritt Sverige	Straw from cereal, energy crops, food waste	The potential could increase with further use of resources/residues from food	9-14 TWh 13-23 TWh	Level of incineration, available agricultural land, and increased possibility for production	Until 2030 and 2045, respectively. Estimated need for biomass 2030 is 193 TWh (increase by 22%). Estimated

				production and production on land in fallow.			need for biomass 2045 135 TWh. Food and feed production are assumed to be at the same level as today.
Hansson, J. & Benders, G.	2015	IVL	mix	The potential is highly dependent on the attractiveness and demand for biofuels. Swedish exports of pellets might grow with increasing sustainability demands.	100-300 EJ Globally/yr	Water assets, land availability, technological innovation for efficiency.	1 EJ is about 278 TWh Wide range in potential due to methodological differences and varying expectations
Hansson, J. et.al	2021	Energiforsk	salix, energy crops, straw and other residues	Possibility to increase the potential in Sweden by using abandoned arable land if the revenue increases		Vegetation season, temperature and rain are the main climate impacts for biofuel production from agriculture.	
Hjort, A.	2019	IVL	organic waste	In previous studies, the estimated potential is about 6 TWh/yr from waste and residues. If no technical limits are included for straw and ILUC-free crops being 4-10 TWh/yr, then the potential could be 10-16 TWh/yr.	1.2-22 TWh/yr	Competing land use, yield, technical limitations, policy tools, price on land	The ratio between theoretical potential and potential is great and show a large uncertainty
Hunhammar, S. et.al.	2021	SOU	straw, manure, sly, intermediate crops	A phasing out of fossil fuel is economically feasible to 2040. Manure will decrease with decreasing bovine kept indoors, as will straw. Sly and other intermediate crops will increase	6.6-9.2 TWh	production techniques, investments and policy tools	technical potential to 2045
IVA	2019	IVA	straw, cereals, legumes, manure, grazing grounds	The greatest potential is achieved if there is better profitability in producing and selling biomass for biofuel.	Swedish production of crops 35-40 TWh	Reclaim fallow, energy crops and increased availability of straw, politics, and policy tools	Seen to the input, every kWh invested in agriculture gives 9.2 kWh in return.
Linné, M. et. Al.	2008	Avfall Sverige	crop residues, manure	There is great potential in using waste streams from industries like crop production, and the total potential is estimated to be around 8 TWh/yr. The counties Skåne	6628 + 4159 GWh/yr (crop residues + manure Sweden)	Competing usage, handling and storage losses. All manure is not available due to gracing.	To achieve the given potential technical development is necessary, collaboration and research.

				and Västra Götaland have a good asset of raw material and greater potential than other counties.			
Norrman, J. et.al	2005	IVL	cereals	There is theoretical potential to cover all of Grästorps energy demand with agricultural biomass.	165 GWh/yr	Need more efficient distribution systems	Energy demand is 25 MWh/pers/yr (600pers), the theoretical potential include higher energy value crops like sugar beets
O'Sullivan Freltoft, A. & Græsted Jensen, I	2021	Energy Modelling Lab	Straw, hay, manure from pets, grass	A great demand is expected from biomass to energy production.	Straw: 19.6, 26.9, 24.9 PJ Grass: -, 19.9, 18.2 PJ Manure from pets: -, 2.0, 2.1 PJ	Limited land area in the country	The total potential of biomass, with no allocation. The estimations are based on the potential from biomass sources that are not used for other purposes such as feed—estimated for 2019, 2030 and 2050.
Pöyry	2019	Pöyry & Nordic Energy Research		Future potential is believed to increase in Finland and Denmark, expected to remain the same in Norway and Iceland and decline in Sweden due to decreasing availability of straw and husk.		A 50% increase in biomass use until 2050 is needed for the carbon-neutral scenario.	Out of current potential: Sweden 43 % Finland 36 % Norway 12 % Denmark 9 % Iceland less than 1 % (Out of current total potential, 20 % is agro biomass, and 10 % is waste).
Riekkola, A. K. et.al.	2017	Energiforsk	*agricultural products not defined*	TIMES-Sweden incorporates the competition between sector and usage. Meanwhile, BeWhere instead depicts different users. The models complement each other.	*5.3 TWh*	TIMES-Sweden shows competition of biomass between electricity production and biofuels	Modell comparison for sectoral usage
Scarlat, N. et.al.	2011	Renewable and Sustainable Energy Reviews	Straw, crop residues and energy crops	There is a significant potential to increase the production of bioenergy in Norway. However, biomass from agriculture plays a minor role in the energy supply.	9 – 19.8 PJ	Abundance and relatively low price on energy from fossil fuels prevent increased bioenergy production. Also, high investment costs slow the transition. Further support and development with mobilisation could drive demand.	The Norwegian bioenergy strategy aims at 100 PJ bioenergy by 2020.

Scott Bentsen, N et.al.	2016	IEA Bioenergy	Straw	Substantial potential to contribute to renewable energy in the future.	65 EJ/yr	Productivity is influenced by yield, size and shape of the field, infrastructure, drying conditions in the field.	Global theoretical potential. The resource density for straw is almost double in Denmark in comparison to southern Sweden, which has a great impact on efficiency in terms of production and transport.
Andersson, L. & Lundin A.	2007	SOU	straw, blast, stubble, chaff, manure, cereals, grazing grounds	There is varying potential amongst regions, and the choice of crop, growing system, ground and geographical location is of great importance.	30 TWh	market, society, goals, policy tools	6-7 TWh from straw 0.5-1 TWh from blast 4-6 TWh from manure economic potential to 2020
Sperling, K. et.al.	2012	Energi princip & Mistra Urban Futures Gothenburg	food waste	Little potential due to urban area	150 GWh	Efficiency in the system	Today 4.7 % of biofuel (236 GWh) From literature, the potential for Sweden 58-165 TWh/yr (2012), 1786-5080 GWh/yr (2050)
Svebio	2020	Svebio	straw, manure, energy crops, grazing grounds	A fossil-free energy system is achievable around 2040.	54 TWH	technology development, competing land use, climate change, market demand, better logistics, use of marginal resources	Today 2 TWH import today 10 TWh increase short time 22 TWH increase long time 54 TWh
Tonini, D et al.	2015	Technical University of Denmark	Straw, grasslands and industrial residues, pig manure		5600 Mkg ww/yr	Crop yield	The assessed biomass in this study is assumed to be wasted if not used in bioenergy production.
Trømborg, E	2015	IEA Bioenergy	Harvesting residues, energy crops	The agricultural biomass potential is limited, mainly due to agricultural land only taking up 3,2 % of the total land area.	8 PJ	The main barriers are relatively low prices of electricity in relation to investment costs and lack of infrastructure.	Theoretical potential for biomass production
Westlund, Å. et.al.	2019	SOU	manure, food waste, energy crops	The potential is significant but uncertain. The capacity to produce is more limiting than the availability of the resource.	30-37 TWh /yr	Competing use of the substrate, population, economic growth, technical development, business models, distribution patterns, climate change, sustainability criteria	technical/practical potential, digestion and lignocellulose combined

A.2. Input data to the BeWhere model

Feedstock production and availability

In the spatial analysis of feedstock production, a 30 km x 30 km grid size is chosen. The grid size gives a total amount of 1770 grids. The availability of feedstock represented at grid level is derived from FAO database on livestock distribution 2010 and agricultural crops, based on the crops harvest area 2015[1]. Data from FAO is represented at 5-arcminute resolution. New grid size is created using reprojection function in QGIS.

The crop production is estimated based on the crop harvested area (GAEZ - harvest area, 2015) and the crop yield grids (GAEZ - crop yield, 2015), both irrigated and rainfed for each crop and grid cell. The energy potential from crops residues is estimated using crop production, residue per product ratio (RPR) and lower heating value (LHV).

Livestock population in Nordic countries

There are seven different types of species that contribute to most of the livestock in the Nordic countries, which are cattle, chickens, ducks, horses, goats, pigs, and sheep. Figure A-1 shows the total number of each livestock in the Nordic Countries. Chicken represents the largest number of livestock (52% of the total livestock), followed by pigs and cattle. The number of goats and horses together is approximately 1% of the total livestock.

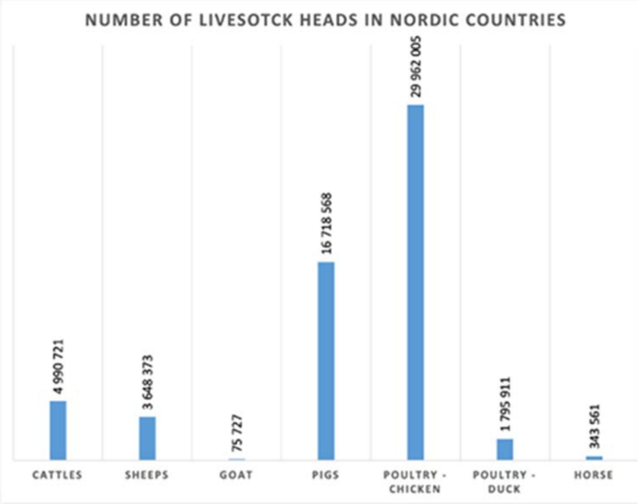

Figure A-1: Total number of livestock heads in the Nordic Countries in 2010

We validated the spatially projected values with the FAOSTAT and found that they are almost all similar, except for poultry. One reason for this is the short live time of these species (less than one year), which makes the values inconsistent. Table A-2 provides the projected values of livestock population in 2020.

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[1] Data Source: https://www.fao.org/faostat/en/#data

Table A-2: Livestock population projected values for 2020

Nordic Country	chicken	pigs	cattle	sheep	horse	ducks	goat	Units
Denmark	16934889.9	12473922	1470977.8	188592.6	40747.8	40143.8	2091.5	heads
Finland	9938521.7	1100294.5	852010.6	127881.1	70312.2	462331.7	425653.8	heads
Iceland	226871.7	27101.6	80705.9	414333.9	66667.4	215718.3	143421.5	heads
Norway	5434711.6	789054.2	881929.7	2293215.9	35254.3	141230.3	144502.7	heads
Sweden	9773619.4	1472435.9	1421123.2	373658.9	93660.7	776806.9	1069.4	heads

Crop production in Nordic countries

Figure A-2 provides the total crop production in the Nordic countries in 2015. Here, we consider the major crops, i.e. wheat, barley, maize, potato & sweet potato, rapeseed, sugar beet, and "other cereals" (includes cereal, rye, oats, triticale, and grain mix). Vegetables, soybean and sunflower are excluded from the study because biogas potential values are not significant due to low production and conversion values.

It can be noticed that wheat represents the largest number of production (32% of the total crop production), followed by barley (25% of the total crop production) and sugar beet (15% of the total crop production). Maize has negligible share in the total crop production

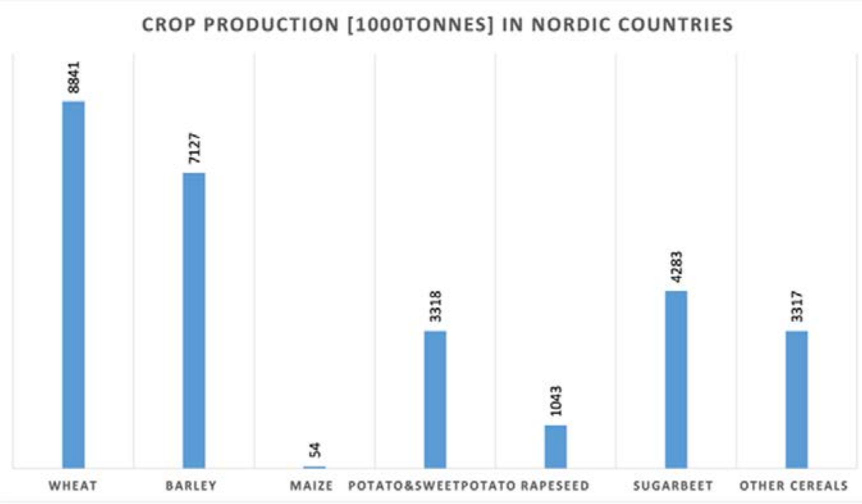

Figure A-2: Total number of crop production in the Nordic countries in 2015

To validate the results obtained in QGIS, they are compared with the FAOSTAT data for the same year (2015) and countries. Table A-3 provides the projected values of crop production in 2020.

Table A-3: Projected values of crop production in 2020 in Nordic countries (Units, 1000 tonnes)

Countries	Wheat	Barley	Cereals	Maize	Potato	Rapeseed	Sugar beet
Denmark	4293.0	3351.9	1031.6	43.4	2487.9	584.4	2964.1
Finland	932.5	1732.8	986.3	0.0	666.7	37.0	666.1
Iceland	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Norway	304.3	550.5	248.1	0.0	275.6	13.2	2.9
Sweden	3196.7	1408.4	1053.1	0.0	817.5	353.1	2825.5

Estimation of agricultural residues and manure for biogas production in Nordic countries

The biogas yield and biomass potential from crop residue in each grid is calculated using the given equations below[2]. The biogas potential of each crop residue in the grid is calculated and then summed up to obtain the total potential in each grid.

$$Practical\ agriculture\ residue\ \left(\frac{kg}{Year}\right) = PAR\ = \sum_{i=1}^{n}(crop(i)_{production} \times RPR(i) \times SRR(i))$$

$$Theoretical\ Biomass\ potential\ \left(\frac{MJ}{year}\right) = \sum_{i=1}^{n}(crop(i)_{production} \times RPR(i) \times SRR(i) \times LHV(i))$$

$$Biogas\ Yield\left(\frac{m3}{year}\right) = \sum_{i=1}^{n}[PAR(i)\left(\frac{kg}{Year}\right) \times TS\%(i) \times VS\ \%(i) * Biogas\ yield(i)\left(\frac{m3}{kgVS}\right)]$$

Where,

$\Sigma\ crop(i)_{production} \times RPR(i)$ is the theoretical biomass

(i=1 to n) is the crop residues from wheat to other cereals

PAR is the Practical Agriculture Residue

SRR is the Sustainable Removal Rate

RPR is the Residue to Product Ratio

Table A-4 provides the characteristics of crop residues for biogas production.

Similarly, the biogas potential from each livestock manure in the grid is calculated and summed up in to obtain the total potential of the grid.

The biogas potential from livestock manure in each grid is estimated as follows[3], also see Table A-5

$$sum_{manure(i)} = Total\ number\ of\ head\ (i) \times Manure\ per\ day \times 365$$

$$Theoretical\ Manure\ potential\ \left(\frac{MJ}{year}\right) = \sum_{i=1}^{n}(sum_{livestock(i)} \times Manure\ per\ day \times LHV(i)) * 365$$

$$Biogas\ Yield\left(\frac{m3}{year}\right) = \sum_{i=1}^{n}[sum_{manure(i)} \times TS\%(i) \times VS\%(i) * Biogas\ yield(i)\left(\frac{m3}{kgVS}\right)]$$

Where,

(i=1 to n) is the livestock from cattle to horse

TS is total solid, VS is volatile solid

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[2] https://www.thaiscience.info/journals/Article/JOSE/10970653.pdf

[3] https://www.sciencedirect.com/science/article/pii/S1364032118304714#bib22

Table A-4: Properties of different crop residues for biogas production.

	Residue to product Ration (RPR)	Sustainable Recovery Rate (SRR)	LHV (MJ/kg)	TS (%)	VS (% of TS)	Biogas yield (m3/kg VS)	Methane yield (m3/kgVS)	References for RPR, SRR, LHV, TS, VS, BG yield and CH4 content
Wheat	0.8-1.6	40%	13.9-19.5	94%	86.80%	0.4	0.24	[4,5,6,7,8,9,10,11]
Barley	0.8-1.3	40%	17.5-19.5	90.50%	94.30%	0.3817	0.229	
Maize	0.9-1.2	50%	13.8-17.6	82%	97.50%	0.583	0.35	
Potato & sweet potato	0.2-0.75	40%	16	25%	95%	0.685	0.411	
Rapeseed	1.4-2	50%	17.1	90.00%	92%	0.4	0.24	
Sugar beet	0.25	50%	15.5-17.7	17%	79%	0.5617	0.337	
other cereals(oats)	0.9-1.4	40%	8.8-19.5	86%	97%	0.6467	0.388	

Note: TS is total solid, VS is volatile solid, BG is Biogas, RPR is Residue to Product Ratio, and SRR is Sustainable Removal Rate

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[4] https://www.sciencedirect.com/science/article/pii/S0956053X10002436?via%3Dihub#tbl3

[5] https://www.sciencedirect.com/science/article/pii/S0960148119300539#bib14

[6] https://www.sciencedirect.com/science/article/pii/S0960852413014855?casa_token=loMELHGTlS4AAAAA:E2MjeFEXqAxqw9s2qKVHUATK1eFFT8wZKdx3kEpI1GhsR9mLa21hFq-LqpyU3lmY7FZ1fZ-oaAY

[7] https://www.sciencedirect.com/science/article/pii/S0960852409018112?casa_token=fE6BUJXK9VYAAAAA:rzBJrPzdbFG4euJhtIQugcMEcBgXz886rv_Vh10vJz2PO9d6ETwBWryiWQGDNRSjmyPUkiCfC3U

[8] https://www.diva-portal.org/smash/get/diva2:1208954/FULLTEXT01.pdf

[9] https://www.sciencedirect.com/science/article/pii/S0960852409018112?casa_token=fE6BUJXK9VYAAAAA:rzBJrPzdbFG4euJhtIQugcMEcBgXz886rv_Vh10vJz2PO9d6ETwBWryiWQGDNRSjmyPUkiCfC3U

[10] https://www.osti.gov/etdeweb/servlets/purl/948934

[11] https://www.engie.com/sites/default/files/assets/documents/2021-07/ENGIE_20210618_Biogas_potential_and_costs_in_2050_report_1.pdf

Table A-5: Properties of different livestock

Livestock	Manure per day (Kg)	Total solid (%)	Volatile Solid (% of TS)	LHV (MJ/kg of dry fuel)	BG yield m^3/kg VS	Methane yield (m3/kgVS)	References for TS, VS, BG yield and CH4 content
Cattles	33.8	9%	80%	17.57	0.355	0.213	[12,13,14 , 15,16,17,18]
Sheep	0.7	30%	80%	14.72	0.4167	0.25	
Goat	1.2	45%	80%	14.95	0.3067	0.184	
Pigs	3	16%	84%	14.46	0.5	0.3	
Poultry - chicken	0.26	42%	76%	14.79	0.41167	0.247	
Poultry - duck	0.26	42%	76%	14.79	0.4117	0.247	
Horse	7	30%	80%	18.14	0.283	0.17	

Note: TS is total solid, VS is volatile solid, BG is Biogas

Conversion technologies: Pathways for conversion of residues and manure

The study considers biogas treatment via co-digestion plant of different raw materials (livestock manure and agricultural residues). The anaerobic digester (AD) is chosen as technology to convert raw material. Raw biogas and bio-digestate are obtained from the AD plant. Figure A-3 provides a schematic diagram of biogas production and use from agriculture residue and livestock manure.

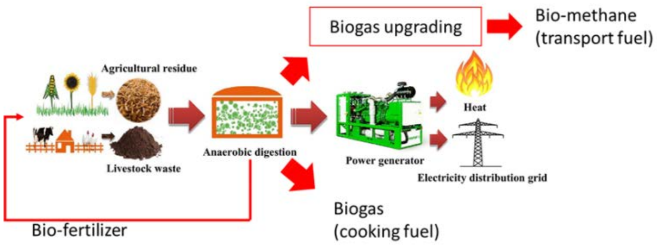

Figure A-3: Schematic diagram of biogas production and use from agriculture residue and livestock manure; Source: adopted with the modification from (Safieddin Ardebili, 2020)[19].

Table A-6 provides the biogas potential and potential of either of the different technologies from each of the livestock in 2020. As mentioned previously, since the data for 2020 is not available, it is estimated by projecting the FAOSTATA data from 2010. It should be noted that cattle and pigs have the highest biogas potential.

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[12] https://www.sciencedirect.com/science/article/pii/S1364032118304714#bib22
[13] https://core.ac.uk/download/pdf/46606176.pdf
[14] https://www.sciencedirect.com/science/article/pii/S1364032118304714
[15] https://uu.diva-portal.org/smash/get/diva2:1355437/FULLTEXT01.pdf
[16] https://www.osti.gov/etdeweb/servlets/purl/948934
[17] http://www.ajfand.net/Volume16/No1/Lars15650.pdf
[18] https://www.engie.com/sites/default/files/assets/documents/2021-05/RI-Engie2021-ENG-vdef.pdf
[19] Safieddin Ardebili, S.M., 2020. https://doi.org/10.1016/j.renene.2020.02.102

Table A-6: Total number of livestock in 2020 and biogas potential from manure

Livestock	Total number of Head (gridded FAO)	Biogas(PJ/Year)	Bio Methane production (PJ/year)	Bioelectricity (PJ/year)	Bioheat (PJ/year)	Theoretical Manure potential (PJ/Year) *)
Cattles	4706747.062	33.13	19.87635364	9.93817682	16.56363	94.88228
Sheep	3648372.681	2.68	1.607239714	0.803619857	1.339366	5.476521
Goat	716738.788	0.75	0.449168295	0.224584147	0.374307	2.111975
Pigs	15862809.08	25.21	15.12754631	7.563773155	12.60629	40.18671
Poultry - chicken	42308614.313	11.39	6.837677307	3.418838653	5.698064	24.94092
Poultry - duck	1636231.008	0.44	0.264438338	0.132219169	0.220365	0.964558
Horse	306642.437	1.151	0.690457699	0.34522885	0.575381	4.263652
Total	69186155.3764	74.75	44.8528813	22.42644065	37.3774	172.8266

*)Direct combustion of manure

Table A-7 describes the biogas potential and potential of different technologies for converting biogas from different crop residues. Here, the values are obtained by projecting 2015 FAOSTAT data. Wheat, barley and other cereals have the highest biogas potential in Nordic.

Table A-7: Total production of crops in 2020 and biogas potential from crop residues

Crop	Production [kg]	Biogas (PJ/Year)	Biomethane (PJ)	Bioelectricity (PJ/year)	Bioheat (PJ/year)	Theoretical Biomass potential (PJ/Year)
Wheat	8614872006	29.15086	17.49052	8.745258	14.57543	69.05681
Barley	6958081017	20.56066	12.3364	6.168198	10.28033	54.06429
Maize	43433196.49	0.229145	0.137487	0.068743	0.114572	0.357998
Potato&sw.pot.	4151084572	2.771553	1.662932	0.831466	1.385776	12.6193
Rapeseed	982758099.1	5.975987	3.585592	1.792796	2.987993	14.28439
Sugar beet	6302634602	1.283632	0.770179	0.38509	0.641816	13.07797
other cereals *)	3302792945	17.70287	10.62172	5.31086	8.851433	21.49788
Total	30355656438.243	77.6747	46.60482	23.30241	38.83735	184.9586

*) values for oats are considered

Table A-8: The consumption of synthesis fertiliser (in tonnes) in the Nordic countries in 2019 (FAO, 2020)

Nutrient	Denmark	Finland	Norway	Sweden	Iceland
Nutrient nitrogen N (total)	224988.8	146798	106765	182664	10381
Nutrient phosphate P2O5 (total)	33803.23	26090.99	20402	29409	1482
Nutrient potash K2O (total)	67002.23	41016	41464	36070	2377

Summary of Biodigester Characteristics and Biodigester estimation

The bio-digestate nutrient content in a typical co-digestion plant with feed materials as wastes from a poultry and dairy farm as well as other imported organic feedstocks such as waste agricultural residues and food wastes can be assumed as mentioned below. The values are finalised based on different case studies on biogas plants in Europe[20].

- N is 8.8% of total solids
- P is 3.6% of total solids
- K is 5.9% of total solids

The total solid content in the bio-digestate is assumed as 10%. Equations used to estimate the total fertilisers are as follows:

$$Biodigester\ =\ 85\%\ of\ the\ total\ feedstock$$

$$Total\ feedstock\ =\ total\ Manure\ +\ total\ practical\ Biomass$$

$$Total\ Biodigester\ =\ 85\% \times Total\ feedstock$$

$$N\ total\ =\ total\ biodigester \times TS\% \times N$$

$$P\ total\ =\ total\ biodigester \times TS\% \times P\%$$

$$K\ total\ =\ total\ biodigester \times TS\% \times K\%$$

From the above calculations, 1 tonne of bio-digestate can give 8.8kg of Nitrogen, 3.6kg of Phosphorous, 5.9kg of potassium

Emissions from AD, CHP, and upgrading plants:

- 0.3% leakage from AD plant and 1.7% of the methane contained in biogas is found in the exhaust gas at CHP plants [21]
- Methane loss 1.57 % in water scrubbing technology[22]

Table A-9: Total estimated emissions from biogas, biomethane and digestate production

Source	Total CH_4 emission(kg/year)	Emission from CH_4 (kg CO_2eq.)
AD plant	8444633.041	211115826
CHP plant	47709361.81	1192734045
Upgrading Plant	44060998.84	1101524971
Digestate	63480650.39	1587016260

*1 kg CH_4:25 kgCO_{2eq}

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[20] circular solutions for Biowaste;Horizon 2020 (https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5bb160f6b&appId=PPGMS)

[21] https://www.sciencedirect.com/science/article/pii/S0961953413000949?via%3Dihub

[22] https://www.sciencedirect.com/science/article/pii/S0956053X19300935

Table A-10: Emission from crops production

Crop	Production in kg	GWP (kgCO2eq/tonne)	Total GWP in (kgCO2eq/tonne)
Wheat	8.84	590.00	5216.19
Barley	7.13	570.00	4062.37
Maize	0.05	184.20	9.87
Potato & sweet potato	3.32	281.00	932.47
Rapeseed	1.04	1480.00	1543.01
Sugar beet	4.28	24.00	102.80
other cereals(oats)	3.32	583.00	1933.91
Total	28.00		13800.63

Table A-11: Emission from livestock production

Livestock	Number of heads	Value: [tonne CO2eq/head]	Total GWP in (kgCO2eq/kg)
Goat	75727.2473	0.31	23475446.67
Duck	1795911.4	0.029	52081430.48
Cattle	4990721	3.492	17427597729
Pig	16718568.3	0.567	9479428198
Sheep	3648372.68	0.31	1130995531
Horse	343561.173	1.277	438727618.3
Chicken	29962005	0.029	868898145.3
Total	57534866.8		29421204098

The total emissions from livestock and crop production calculated for all the Nordic Countries are expressed in Table A-12.

Table A-12: Calculated emissions from livestock and crop production (in million tons CO2eq) in the Nordic countries

Countries	Emissions from livestock	Emissions from crop production	Total emissions
Denmark	13.24	6.74	19.98
Finland	4.84	2.37	7.21
Iceland	0.54	0.00	0.54
Norway	4.48	0.70	5.18
Sweden	6.91	3.99	10.90

Land, water and energy use in the agriculture sector in the Nordic countries

Table A-13: Land-use in all the Nordic countries in 2019[23]

	Norway		Sweden		Denmark		Finland		Iceland	
Land use	km2	%	km2	%	km2	%	km2	%	km2	%
Total land area (incl. freshwater)	625.218		528.86106		42.92		338.460		103	
Agriculture	9.81822	2%	30.0478	6%	26.26	61%	22.740	7%	18.720	18%
Forest	121.722	19%	279.8	53%	6.275	15%	224.090	66%	0.5069	0%
Other land ar.	233.5532	37%	97.43579	18%	7.4613	17%	57.100	17%	81.6031	79%
Water area	260.124	42%	121.57747	23%	2.92	7%	34.530	10%	2.170	2%

Table A-14: Water and energy use in the Nordic countries in the agriculture Sector

Countries	water use [billion cubic meters]	Year	Countries	Energy Usage [TJ]	year
Sweden[24]	0.098	2010	Sweden[25]	24367	2019
Denmark[26]	0.315	2020	Denmark[27]	26376	2019
Finland[28]	0.05	2007	Finland[29]	38603	2020
Iceland[30]	0.07	2006	Iceland[31]	1833	2019
Norway[32]	0.8449	2004	Norway[33]	25200	2020

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[23] *https://www.fao.org/faostat/en/#data/RL*

[24] https://www.scb.se/en/finding-statistics/statistics-by-subject-area/environment/water-use/water-withdrawal-and-water-use-in-sweden/pong/statistical-news/water-abstraction-and-water-use-in-sweden-2015/

[25] https://www.statista.com/statistics/1025137/net-consumption-of-electricity-in-norway-by-user/

[26] https://www.dst.dk/en/Statistik/emner/miljoe-og-energi/groent-nationalregnskab/vand-og-spildevand

[27] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_energy_use#Analysis_at_EU_and_country_level

[28] https://www.worldometers.info/water/finland-water/#water-use

[29] https://stat.luke.fi/en/energy-consumption-of-agriculture-and-horticulture

[30] https://www.worldometers.info/water/iceland-water/

[31] https://www.nordicstatistics.org/environment-and-energy/energy-use-and-supply/

[32] https://www.worldometers.info/water/norway-water/#water-use

[33] https://energifaktanorge.no/en/norsk-energibruk/energibruken-i-ulike-sektorer/

A.3. CLEWs scenarios and exploration of future biogas production

Table A-15: Livestock population values from 2015 to 2050 in all Nordic Countries for the "Towards Sustainability Scenario"

Year	cattle [1000heads]	pig [heads]	sheep [heads]	goat [heads]	poultry [heads]
2015	4939	16368	3119	64	38433
2020	4927	16854	3123	62	38680
2025	4834	16876	3075	59	38288
2030	4711	16756	3002	56	37611
2035	4561	16614	2920	53	36733
2040	4393	16494	2842	49	35800
2045	4231	16437	2776	46	34973
2050	4092	16445	2726	44	34329

Table A-16: Crop production values from 2015 to 2050 in all Nordic Countries for the "Towards Sustainability Scenario"

Year	barley [1000heads]	potato [1000heads]	maize [1000he.]	rapeseed [1000heads]	sugar beet [1000he.]	wheat [1000he.]	other cereals [1000he.]	vegetables [1000he.]
2015	7827364.48	3564786.56	68637.12	1148323.05	5492431	7973535.66	3507810	1158190.3
2020	7928725.97	3738964.64	67884.62	1130318.51	5776357.77	8121303.28	3588784	1223061.3
2025	7831361.68	3825040.54	66336.91	1085244.37	5894094	8047195.85	3539271	1232127.1
2030	7722609.61	3931193.01	64947.93	1047504.26	6029879	7947584.94	3502454	1245509.7
2035	7780936.06	4112570.88	64840.93	1038154.8	6189616	7976029.16	3536603	1280319.6
2040	7931209.71	4345810.35	65449.34	1040808.42	6381476	8093263.6	3620630	1327543.7
2045	8120765.22	4595088.05	66083.5	1046875.11	6565124	8242083.1	3720500	1375433.8
2050	8358784.01	4840416.19	66884.21	1052208.63	6721172	8402919.6	3841536	1418948.8

Table A-17: Livestock population values from 2015 to 2050 in all Nordic Countries for the "Stratified Societies Scenario"

	cattle [1000heads]	pig [heads]	sheep [heads]	goat [heads]	poultry [heads]
2015	4813	16262	3162	63	37571
2020	4673	16688	3220	61	36990
2025	4482	16823	3214	57	35964
2030	4321	16909	3187	54	35117
2035	4270	17100	3169	52	34824
2040	4276	17407	3160	51	34950
2045	4305	17777	3148	50	35324
2050	4339	18172	3129	49	35840

Table A-18: Crop production values from 2015 to 2050 in all Nordic Countries for the "Stratified Societies Scenario"

	barley [1000he.]	potato [1000he.]	maize [1000he.]	rapeseed [1000he.]	Sugar beet [1000he.]	wheat [1000he.]	Other cer. [1000he.]	vegetables [1000he.]
2015	8343546	3762575	73141	1194229	5721143	8386541	3699770	1213341
2020	9307291	4297812	80333	1257464	6461703	9272210	4100182	1383855
2025	10166455	4808120	87875	1305102	7133079	10055543	4391019	1499127
2030	10865178	5315214	94598	1335899	7802165	10693876	4627760	1606590
2035	11366940	5781290	100178	1370686	8362399	11194729	4778783	1700518
2040	11748558	6237005	104888	1399982	8886140	11625056	4879321	1786103
2045	12080243	6700204	109310	1427241	9377515	12011451	4968316	1867706
2050	12437026	7181420	114061	1456238	9846014	12400736	5069964	1947482

The results of the two different CLEWs Scenarios: "Towards sustainability" and "Stratified Societies" are presented in Figure A-4, Figure A-5, Figure A-6 and Figure A-7.

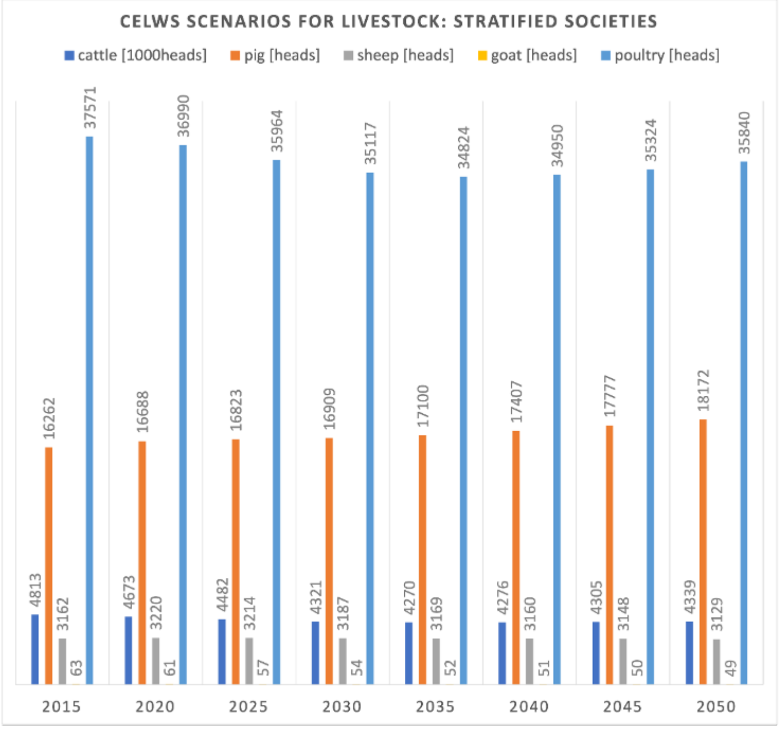

Figure A-4: Livestock values for "stratified societies" scenario from 2015 to 2050 for the Total Nordic region

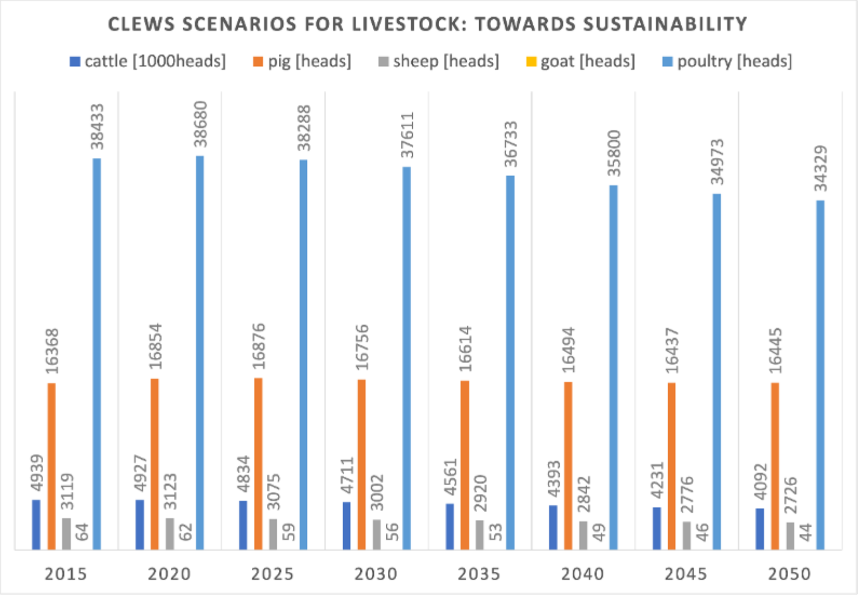

Figure A-5: Livestock values for "towards sustainability" scenario from 2015 to 2050 for the Total Nordic Region

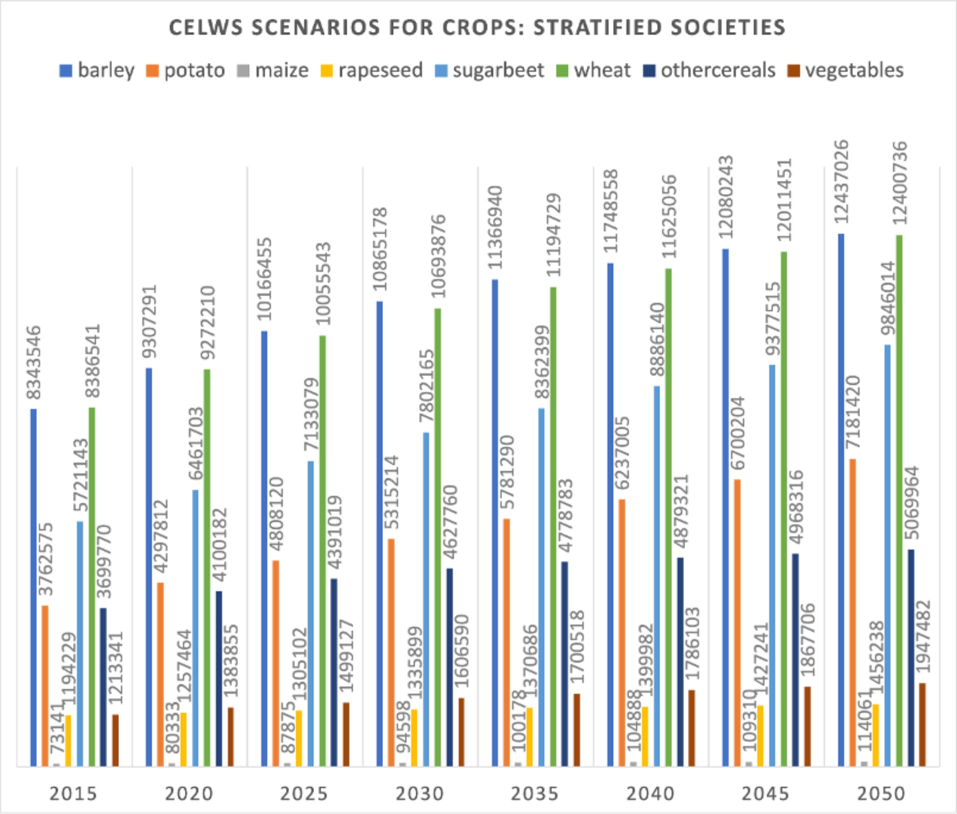

Figure A-6: Crop production values for "stratified societies" scenario from 2015 to 2050 for the Total Nordic Region

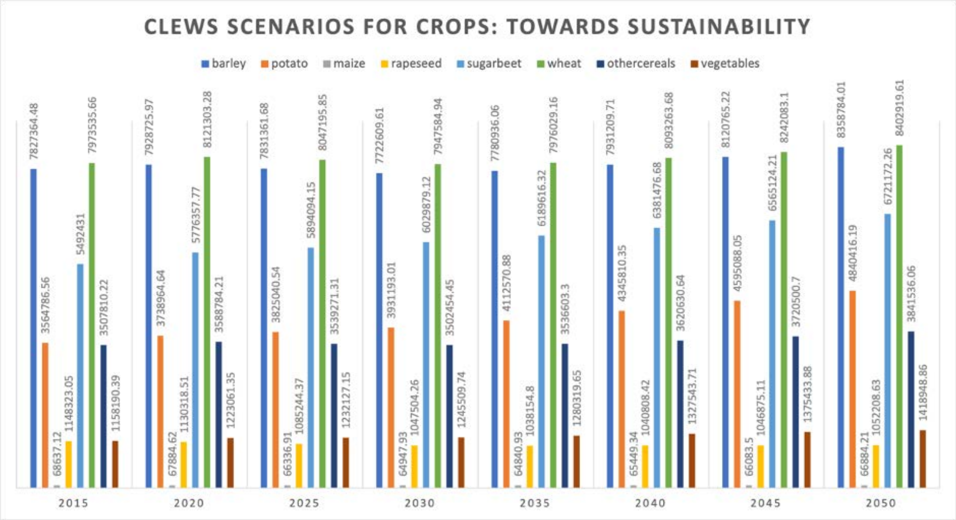

Figure A-7: Crop production values for "towards sustainability" scenario from 2015 to 2050 for the total Nordic region

[1] Data Source: https://www.fao.org/faostat/en/#data

[4] https://www.sciencedirect.com/science/article/pii/S0956053X10002436?via%3Dihub#tbl3

[5] https://www.sciencedirect.com/science/article/pii/S0960148119300539#bib14

[6] https://www.sciencedirect.com/science/article/pii/S0960852413014855?casa_token=loMELHGTlS4AAAAA:E2MjeFEXqAxqw9s2qKVHUATK1eFFT8wZKdx3kEpI1GhsR9mLa21hFq-LqpyU3lmY7FZ1fZ-oaAY

[7] https://www.sciencedirect.com/science/article/pii/S0960852409018112?casa_token=fE6BUJXK9VYAAAAA:rzBJrPzdbFG4euJhtIQugcMEcBgXz886rv_Vh10vJz2PO9d6ETwBWryiWQGDNRSjmyPUkiCfC3U

[9] https://www.sciencedirect.com/science/article/pii/S0960852409018112?casa_token=fE6BUJXK9VYAAAAA:rzBJrPzdbFG4euJhtIQugcMEcBgXz886rv_Vh10vJz2PO9d6ETwBWryiWQGDNRSjmyPUkiCfC3U

[10] https://www.osti.gov/etdeweb/servlets/purl/948934

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[17] http://www.ajfand.net/Volume16/No1/Lars15650.pdf

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[21] https://www.sciencedirect.com/science/article/pii/S0961953413000949?via%3Dihub

[22] https://www.sciencedirect.com/science/article/pii/S0956053X19300935

[23] *Data Source: https://www.fao.org/faostat/en/#data/RL*

[24] https://www.scb.se/en/finding-statistics/statistics-by-subject-area/environment/water-use/water-withdrawal-and-water-use-in-sweden/pong/statistical-news/water-abstraction-and-water-use-in-sweden-2015/

[25] https://www.statista.com/statistics/1025137/net-consumption-of-electricity-in-norway-by-user/

[26] https://www.dst.dk/en/Statistik/emner/miljoe-og-energi/groent-nationalregnskab/vand-og-spildevand

[27] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_energy_use#Analysis_at_EU_and_country_level

[28] https://www.worldometers.info/water/finland-water/#water-use

[29] https://stat.luke.fi/en/energy-consumption-of-agriculture-and-horticulture

[30] https://www.worldometers.info/water/iceland-water/

[31] https://www.nordicstatistics.org/environment-and-energy/energy-use-and-supply/

[32] https://www.worldometers.info/water/norway-water/#water-use

[33] https://energifaktanorge.no/en/norsk-energibruk/energibruken-i-ulike-sektorer/

A.4. Communication with the Ministry of Climate and Environment

" EU-landene skal i henhold til EUs styringssystem (Governance Regulation EU 2018/1999) levere National Energy and Climate Plans (NECPs). Denne rettsakten er ikke tatt inn i EØS-avtalen i sin helhet, og Norge er derfor ikke forpliktet til å utarbeide NECPs i tråd med reglene i forordningen. Med andre ord, Norge har ikke formelt sett en NECP.

Da Norge inngitt den såkalte «klimaavtalen med EU» tok vi imidlertid inn enkelte bestemmelser fra EUs styringssystem som gjelder klimarapportering. I tillegg ble det enighet om at Norge og Island på frivillig grunnlag skulle vise hvordan vi vil nå forpliktelsene i regelverket for ikke-kvotepliktig utslipp (innsatsfordelingsforordningen) og regelverket for skog- og arealbruk (LULUCF-forordningen). Planen du viser til under var den planen forrige regjering sendte inn til ESA i desember 2019. Hva en slik frivillig plan skulle inneholde følger av en frivillig erklæring som er tatt inn i EØS-komitébeslutningen om «klimaavtalen med EU»: 269-2019.pdf (efta.int). Den forrige regjeringen la også i 2021 frem "Klimaplan for 2021-2030". ESA har laget en «progress report» for Norge og Island som også baserer seg på Norges rapportering på klimaavtalen, rapporten er tilgjengelig her: ESA Climate Progress Report 2021 Final version.pdf (eftasurv.int).

For å oppsummere: Norge leverer ikke en NECPs, men har på frivillig grunnlag levert en «plan» som skal vise hvordan Norge skal nå forpliktelsene i regelverket for ikke-kvotepliktige utslipp og skog- og arealbruk i 2019. Siden Norge ikke er formelt forpliktet til å levere en oppdatert plan, har ikke «Klimaplanen for 2021-2030» blitt levert som Norges nye plan, men ESA er orientert om at den finnes. I praksis vil ESA få informasjon om Norges klimapolitikk og fremgang mot våre forpliktelser gjennom klimarapporteringen som vi er forpliktet til å levere til ESA 15. mars annethvert år. "