ENVIRONMENTAL AND SOCIO-ECONOMIC ANALYSIS OF INTEGRATED GRASS BIOREFINERY SCENARIOS

Scientific Report from DCE – Danish Centre for Environment and Energy No. 383 2020

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Data sheet

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Abstract:	This report presents financial and welfare economic analyses of two scenarios for production of green proteins at a biorefinery, integrated with a biogas facility. Residual biomass resources from the protein production provides input to biogas generation, which in turn supplies process energy for the biorefinery, while surplus biogas is upgraded to biomethane. The protein production is based on highly fertilized grasses (450 kgN/ha) that replace conventional crops. The externalities considered in the welfare economic analysis comprise GHG emissions, air pollution, N and P leaching, cadmium as well as road and off-road transport. The analysis shows that protein production in association with biogas generation, based on biomass input of highly fertilized grass, can be commercially attractive, though depending on scale and the specific assumptions made. However, from a public expenditure perspective such production will be burdensome, due to the generous feed-in tariffs awarded to biogas. The negative outcome of the welfare economic analysis indicates that environmental benefits to Denmark do not suffice to justify the level of public support that would be involved. However, the economic value of a potential GHG reduction from less import of soy has not been included, due to its non-domestic features and the uncertainties involved.
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Contents

List of abbreviations

CHP: Combined Heat and Power

CM: Contribution Margin

DM: Dry Matter

ETS: Emissions Trading System

GHG: Green House Gas

JB: Soil type. Referring to Danish classification system for agricultural soils.

LHV: Lower Heating Value

Preface

This report has been prepared as part of the research project ”Environmental and socio-economic consequences of innovations for increased biomass production and –utilisation in Denmark” (ECOECO), one of four projects constituting the BIOBASE research platform at Aarhus University, Faculty of Science and Technology.

The biorefinery setup envisioned in relation to the green protein extraction from grasses has been pioneered at pilot scale by senior scientist Henrik B. Møller and assistant professor Morten Ambye-Jensen, Dept. of Engineering. The pilot project, which has been reported elsewhere (Hermansen et al., 2017), has provided experiences and insights used in the upscaling of costs for more large-scale implementation of green protein production technologies. The costs used in the present report have been estimated by us in collaboration with assistant professor Morten Ambye-Jensen, Dept. of Engineering. The specific estimations of the road transport requirements and costs have been prepared by senior researcher Claus Aage Grøn Sørensen, Dept. of Engineering.

In accounting for the environmental and socio-economic consequences we base our estimations on insights obtained from lifecycle analyses of the biorefinery and the implications at farm level for substituting cereals with grass. The LCA data (see annex 4) was prepared by senior researcher Marie Trydeman Knudsen, associate professor Lisbeth Mogensen and postdoc Sylvestre Njakou Djomo, Dept. of Agroecology, to whom we are grateful for their support to the project.

The budget and welfare economic analyses have been conducted in accordance with the standard methodologies for economic impact assessments developed in Denmark, and follow the guidelines issued by the Danish Ministry of Finance.

We are grateful for comments and suggestions to the report from senior researcher emeritus John Hermansen, project instigator of the ECOECO project. The responsibility for the final economic assessment, as based on the deliveries from other BIOBASE partners and work packages, rests with the authors.

Roskilde and Aarhus, June 2020

Sammenfatning

Denne rapport præsenterer budget- og samfundsøkonomiske analyser af to scenarier for produktion af grøn protein. Scenarierne er defineret som de mest relevante ud fra den viden, der var tilgængelig ved projektets start, og er ikke udtryk for en optimering baseret på de opnåede resultater.

Fælles for scenarierne er, at produktionen af grønt protein sker på bioraffinaderier, hvor produktionen er integreret med produktionen af biogas, således at synergier mellem de to processer kan udnyttes. Restprodukter fra protein produktionen anvendes som input til produktionen af biogas, der efterfølgende anvendes som procesenergi på bioraffinaderiet. I begge scenarier opgraderes overskydende biogas til biometan, som sendes ud på distributionsnettet, hvor den erstatter naturgas. Proteinproduktionen er baseret på intensivt gødet græs (450 kgN / ha), der fortrænger hidtidig kornproduktion. Analyserne tager så vidt muligt højde for de landbrugsrelaterede effekter af den ændrede produktionssammensætning.

De to analyserede scenarier adskiller sig fra hinanden i forhold til produktionskapacitet, biogasrelateret investeringsbehov, samt anvendelse af restfraktionerne fra proteinproduktionen. I det ene scenarie er bioraffinaderiet skaleret i forhold til et årligt græsinput på 20.000 ton tørstof, og det er udelukkende væskerestfraktionen fra proteinproduktionen, der anvendes til biogas, idet fiberrestfraktionen antages at kunne afsættes som kvægfoder. Proteinanlægget antages lokaliseret i tilknytning til et eksisterende biogasanlæg med opgraderingsfaciliteter, hvor der antages at være en uudnyttet overkapacitet, som betyder, at de biogasrelaterede investeringsomkostninger er begrænsede. Det andet scenarie er specificeret som et storskala proteinanlæg med et årligt græsinput på 150.000 ton. Her anvendes både væske- og fiberrestfraktionerne til biogas, og de biogasrelaterede investeringsomkostninger er betydeligt højere end i det første scenarie, idet det er nødvendigt at etablere et nyt biogasanlæg.

De budgetøkonomiske analyser viser, at det lille anlæg giver overskud for bioraffinaderiejerne, hvorimod storskala anlægget giver underskud. I begge tilfælde er netto-resultatet imidlertid relativt tæt på break-even, og den usikkerhed der er forbundet med mange af de opgjorte indtægter og omkostninger betyder, at resultaterne nærmere skal tolkes som et udtryk for den forventede størrelsesorden af nettoresultaterne, frem for en eksakt opgørelse af rentabiliteten af hhv. små- og storskala grøn protein bioraffinaderier. Forskellen i anvendelsen af restprodukter, samt antagelserne vedr. behovet for biogasrelaterede investeringer betyder, at der er forskel mellem de to scenarier ift. den relative betydning af forskellige udgifts- og indtægtsposter. Græs repræsenterer den væsentligste omkostningspost i begge scenarier, men udgør en relativt større del af de samlede omkostninger for det lille anlæg end for det store, hvor investeringsomkostninger omvendt udgør en ca. dobbelt så stor andel af de samlede omkostninger som i småskalascenariet. På indtægtssiden bidrager tilskud henholdsvis salg af produkter hver med ca. 50 % i storskalascenariet, hvorimod tilskud kun udgør ca. 10 % af indtægterne i småsskalascenariet, og hvor indtægter fra salg af fiberfraktionen til kvægfoder tegner sig for ca. 50 % af indtægterne. Indtægter fra salg af proteinproduktet udgør 30-35 % af de samlede indtægter i begge scenarier.

Set fra et statsfinansielt synspunkt resulterer begge scenarier i betydelige underskud, men størrelsen af underskuddet varierer, og er således godt 5 gange større per input enhed (græs som tørstof) for storskalaanlægget end for det lille anlæg. Det statsfinansielle underskud skyldes det høje tilskudsniveau til biogasproduktion. Forskellen mellem de to scenarier skyldes især, at den tilskudsberettigede biogasproduktion per ton tørstof i input til bioraffinaderiet er væsentligt større i storskalascenariet, hvor både fiber og væskefraktionen bruges til biogas, end i småskala scenariet, hvor det kun er væskefraktionen, der anvendes til biogas.

Set fra et velfærdsøkonomisk synspunkt giver begge scenarier anledning til underskud. Underskuddet per ton tørstof input er dog ca. 10 gange større i storskalascenariet end i småskalascenariet. Den relative betydning af de forskellige omkostningskomponenter er den samme som i den budgetøkonomiske analyse. Da statslige tilskud imidlertid ikke medtages i den velfærdsøkonomiske analyse, medfører det ændringer i den relative betydning af de forskellige indtægtskomponenter. I småskalascenariet er fiberfraktionen stadig den væsentligste indtægtskilde (ca. 55 %), efterfulgt af proteinproduktet (ca. 40%). I storskalascenariet tegner proteinproduktet sig for ca. 60 % af indtægterne, mens biometan og afgasset biomasse bidrager med hhv. 23 og 14 %.

Nettoværdien af de eksterne effekter er negativ i begge scenarier, men den er 3-4 gange højere i storskalscenariet end i småskalascenariet per ton tørstof. Relativt set har de eksterne effekter dog en større betydning for nettoresultatet af småskalascenariet, idet underskuddet per enhed input (ekskl. eksterne effekter) er væsentlig mindre end i storskalascenariet. De inkluderede eksterne effekter omfatter drivhusgasemissioner (GHG), luftforurening, kvælstof (N) og fosfor (P) udvaskning, cadmium, og transport. I småskalascenariet er der positive eksterne effekter i fht. N- og P-udvaskning, samt reduceret markarbejde (ikke-vej transport); de andre eksterne effekter er negative, og de betydeligste bidrag kommer her fra øgede emissioner af GHG og ammoniak, og øgede emissioner fra transport af græs fra mark til bioraffinaderi. I storskalascenariet sker der en reduktion i GHG-emissionerne, som sammen med de beskedne reduktioner i P-udvaskningen og emissionerne fra markarbejdet bidrager positivt til det velfærdsøkonomiske resultat. De resterende eksterne effekter har imidlertid negativ effekt på det samlede resultat. Den økonomiske værdi af eventuelt færre drivhusgasreduktioner ved mindre import af soja er ikke medtaget i analysen, eftersom denne sker uden for Danmark og må anses for usikker.

Samlet set indikerer analyserne, at proteinproduktion koblet med produktion af biogas, baseret på input af intensivt gødet græs kan være rentabel set fra et privatøkonomisk synspunkt, men at det i høj grad afhænger af skalaen af produktionen, samt af de mere specifikke antagelser, der lægges til grund for analysen. Set fra et statsfinansielt synspunkt er produktionen imidlertid en underskudsforretning jf. de høje tilskud, der p.t. gives til biogasproduktion. I forlængelse heraf indikerer resultaterne af den velfærdsøkonomiske analyse, at værdien af de eksterne effekter ikke kan bruges som argument for hverken at øge eller bibeholde det nuværende høje tilskudsniveau. Der kan imidlertid være andre hensyn, eksempelvis forventning om fremtidig teknologisk udvikling eller optimering af udnyttelsen af restprodukter, som kan begrunde bibeholdelse af et højt tilskudsniveau.

Summary

This report presents financial and welfare economic analyses of two scenarios for production of green proteins. The scenarios have been defined as the most relevant based on the knowledge available at the time of the project inception, and thus do not reflect an optimization based on the current results.

The two scenarios feature production of green protein at a biorefinery, integrated with a biogas facility, and with some synergies exploited. Residual biomass resources from the protein production provides input to biogas generation, which in turn supplies process energy for the biorefinery. Surplus biogas is upgraded to biomethane and is fed into the general gas grid, substituting natural gas. The protein production is based on highly fertilized grasses (450 kgN / ha) that supplant conventional crops. The analyses include and reflect the agricultural implications of changes in land use.

The two scenarios differ with regard to overall production volume, biogas investment needs and the use of protein production residuals. One scenario features a smaller biorefinery, scaled according to an annual grass input of 20,000 tonnes of dry matter, and with only the juice fraction being supplied to the biogas plant, while fiber residuals are sold for cattle feed. In this scenario the protein plant is localized in the vicinity of an existing biogas plant with upgrading facilities, on the assumption of excess capacity, whereby investment needs are limited. Another scenario features a large-scale protein plant with an annual grass input of 150,000 tonnes of dry matter. In this case residuals of both juice and fiber are used for biogas generation, with significant investments required for a new biogas plant.

The financial analysis shows that the small-scale plant can generate a surplus to the biorefinery owners, while the large-scale plant will be making losses. Still, both scenarios feature net results relatively close to a break-even, and the uncertainties associated with several cost and income components imply that the results should be seen as an approximation, rather than representing exact figures for the profitability of small- and large-scale green protein biorefineries.

Deviations in use of residual products along with the assumptions on the need for biogas investments create differences in the significance of individual cost and revenue components. Grass biomass constitutes the single most important cost item in both scenarios, though in relative terms its share is greater in the small-scale scenario. The large-scale scenario features more substantial investment costs, in relative terms more than twice the share in the small-scale scenario. With regard to revenues, subsidies and product sales each generate about half the income in the large-scale scenario, whereas in the small-scale scenario subsidies are less important, securing only about 10 % of revenues, while incomes from sales of fibers for cattle feed bring about 50 %. Revenues from the protein product constitute about 30-35 % of income in both scenarios.

With regard to public expenditures, both scenarios involve considerable spending, though of different magnitudes; it is about five times higher per tonne of dry matter for the large-scale plant due to both juice and fiber being supplied for generation of biogas. The small-scale scenario has less biogas

generation as only the juice fraction is used. This public spending is due to the generous subsidies (feed-in tariffs) available for biogas.

Both scenarios result in a negative welfare economic result. The outcome per tonne dry matter is about ten times less in the small-scale scenario, however. The relative significance of the various cost items is similar to findings in the financial analysis, while with subsidies excluded, some changes appear in the relative significance of the income components. The fiber fraction remains the most important source of revenue (57 %) in the small-scale scenario, with the protein product in second place (39 %). In the large-scale scenario, the protein product accounts for 63 % of incomes, with biomethane and degassed biomass accounting for 23 and 14 % respectively.

The net value of externalities is negative in both scenarios; however they become more significant to the final outcome of the small-scale scenario, due to a lesser deficit prior to externalities. The externalities considered in the analysis comprise GHG emissions, air pollution, N and P leaching, cadmium as well as road and off-road transport. The small-scale scenario involves positive externalities from reduced N and P leaching as well as from less off-road transport, but the remaining environmental impacts are all negative, with GHG, ammonia and road transport dominating. The large-scale scenario sees a reduction in GHG emissions (due to higher biogas generation), along with less P leaching and off-road transport, but the remaining externality components serve to offset these, rendering the final result negative in monetary terms. The economic value of a potential GHG reduction from less import of soy has not been included, due to its non-domestic features and the uncertainties involved.

In summary, the analysis shows that protein production in association with biogas generation, based on biomass input of highly fertilized grass, can be commercially attractive, though depending on scale and the specific assumptions made. However, from a public expenditure perspective such production will be burdensome, due to the generous feed-in tariffs awarded to biogas. The welfare economic analysis shows that the aggregate externality balance does not suffice to justify the level of public support that would be involved. Still, other considerations, i.e. related to potentials for future technological developments or novel markets for the residual products, might provide reasons for maintaining the high level of public support.

1 Introduction

Danish and European livestock production relies to a great extent on import of soy protein from South America. There are significant environmental concerns related to production of soy from areas where rain forest is cleared, due to impacts on biodiversity and land use changes causing emissions of greenhouse gases.

To reduce such negative indirect impacts of livestock production, research has been devoted to increase domestic production of protein-rich feed for non-ruminant livestock. One option in focus is to extract protein from grass. Until now, grass based provision of protein has been limited to small-scale pilot plants, but large-scale production should be technically feasible within the foreseeable future. To facilitate upscaling of grass based protein extraction, the Danish government has recently granted 8 million DKK to a demonstration biorefinery plant, where protein, green fodder and biogas is to be produced jointly based on clover and grass[1].

The production of green protein from grass in a temperate climate – as in Denmark – represents potentially a significant environmental benefit (Concito, 2014). First, it is possible to obtain a higher protein yield per ha than from soy in the current production, and at the same time a higher production of biomass than from cereals, diminishing the pressure on global land use and land use changes and the related impact on biodiversity and emissions of greenhouse gases. Second, grass production represents from a national perspective a significant potential as a means to reduce N leaching and increase soil carbon sequestration as compared to the cereal production that would otherwise take place on farmland (Hermansen et al., 2017).

While considerable efforts have been devoted to optimise production processes and assess environmental impacts, less attention has up to now been devoted to analyse the economics of green protein production.

Termansen et al. (2015) present preliminary economic analysis of two different green protein scenarios; a centralised, large-scale plant scenario, with an annual processing capacity of 150,000 tonnes grass (dry-weight) and a decentralised, small-scale plant scenario with an annual processing capacity of 20,000 tonnes grass (dry-weight). In both scenarios, the production of protein is combined with biogas production. Both scenarios are found to be commercially viable with internal rates of return at 11 % (large-scale scenario) and 68 % (small-scale scenario). The economic analysis of Termansen et al. (2015) does not consider environmental aspects.

Cong and Termansen (2016) analyse the economics of green protein production combined with biogas, and present detailed models of the livestock feed substitutions following the introduction of novel green protein feedstock. In contrast to Termansen et al. (2015), Cong and Termansen (2016) include some environmental impacts, while also presenting sensitivity analysis. Their findings suggest that green protein production will be profitable for the biorefinery operators, while lowering feeding costs and reducing N leaching. The

[1] See: http://mfvm.dk/nyheder/nyhed/nyhed/millioner-skal-goere-landbruget-mere-klimavenligt/

analysis considers a scenario where grass silage is used for protein production, whereas the fibre fraction is used for high-value insulation products. Currently, however, there is no commercial market for the type of fibre insulation and current production technologies require fresh grass as input. Additional analyses are required in order to determine if the green protein production scenarios considered are economically attractive, both seen from the financial perspective of investors and stakeholders and from the welfare economic perspective.

The present report presents detailed economic analysis of two different scenarios of green protein production at commercial scale, thereby addressing the research lacunae identified above. Both scenarios involve joint production of protein and biogas, and the combined plants are referred to as a biorefinery. The analysis is conducted as part of a larger research project on Green Protein Production under the BIOBASE research platform (http://projekter.au.dk/en/import/biobased-production/research-platforms/), with several work-packages analysing different aspects of the production process. Jointly the work-pages are intended to produce a comprehensive and coherent framework for identifying technical, environmental as well as economic challenges and potentials of green protein production. A parallel project (See e.g. http://orgprints.org/31685/1/OrganoFinery.html) is analysing the feasibility of green protein production in the context of organic farming, where challenges in ensuring sufficient supply of feed and non-conventional fertilizer makes production of green protein interesting. In the present report, focus is on the implications of green protein production within conventional agriculture.

The scenarios analysed in this report have been defined in collaboration with other BIOBASE work-packages to ensure consistency in the underlying assumptions, and to ensure that the scenarios are relevant and up to date in terms of the technological, environmental and economic assumptions. Thus, the scenarios are expected to reflect green protein biorefinery concepts currently considered the most relevant in a Danish context. Specifically, it should be noted, that the analysed scenarios correspond to an Integrated Green BioRefinery (IGBR) scenario, which has been found to be more efficient than a Standalone Green BioRefinery scenario (SGBR) in previous Life-Cycle Assessments (Njakou Djomo et al., 2020). As experiences with protein production remain at pilot scale, the scenarios are hypothetical. The analysis is based on a number of assumptions of which several are associated with significant variability, causing a significant amount of uncertainty. A related aim is thus to identify key-determinants to the financial and welfare economic feasibility of green protein production. A separate chapter is devoted to analyse and consider the sensitivity of results to changes in underlying assumptions.

The remainder of the report is structured as follows. Chapter 2 contains a general introductory description of the scenarios subject to analysis. Chapter 3 contains a detailed description of the production taking place at the grass refinery, including an account of the production of input to the protein production. Chapter 4 contains a detailed description of the production taking place at the biogas plant, including a description of the substitutions in the energy production system following the increased production of biogas. In Chapter 5 focus is on the external impacts associated with both scenarios. Accordingly, chapters 3-5 are structured according to the various stages of the production processes and with respect to the sectors affected. In these chapters, the two scenarios are presented and analysed in parallel, facilitating comparison across scenarios, which also helps illustrate how different assumptions inflict on the economic profitability of green protein production. Based on the previous chapters, the overall financial and welfare economic profitability of the two scenarios is presented and discussed in Chapters 6 and 7. Subsequently, the results and their sensitivity to changes in the factors identified as key-determinants to the economic profitability of the scenarios is discussed in Chapter 8. Chapter 9 concludes on the analysis and place findings in a wider perspective.

2 Scenarios

Two scenarios of commercial scale biorefineries are analysed in the report. Both scenarios are compared to a baseline scenario without any such biorefinery. One scenario involves a large protein production plant with an annual processing capacity of 150,000 tonnes dry matter, located in the southwestern part of Zealand (on the border of the Slagelse and Næstved municipalities). The other scenario involves a small-scale protein production plant with an annual processing capacity of 20,000 tonnes dry matter located in the northern part of Jutland (on the border between the Vesthimmerland, Rebild and Mariager municipalities). The two case study areas differ in terms of livestock density, soil types and arable crop choices, which are factors that are integrated into the scenarios.

In both scenarios, the production of protein is based on input of high yielding grasses, cultivated in the vicinity of the biorefineries. The grass is assumed to be cultivated with use of mineral fertilizers and on fields located within an average distance of 10 km from the protein plant in the large-scale scenario, and with an average distance of 5 km for the small-scale scenario. The difference reflects that more land is needed to produce the required amount of input for the large-scale plant. The production of grass for the protein plants is assumed to displace previous production of spring barley and winter wheat, while ensuring sufficient land with cereal production to allow for an appropriate crop-rotation. In order to ensure a satisfactory quality of the protein product, it is important that the grass is processed immediately after harvest; hence, the grass cannot be ensiled and stored for later use. This implies that the protein plant only operates during the grass harvest season running from May through October. The remaining half of the year the plant is idle.

The primary product is the protein product, which – in contrast to grass - can be used as feed for non-ruminant animals, substituting previous use of soy. The protein product can either be used directly for wet feeding, or it can be dried and used as dry feed. If used for wet feeding, the protein product needs to be used within a fairly short period of time. If dried, the shelf-life of the product is significantly prolonged; also the moisture content of the product is reduced, which helps reduce the transport costs associated with bringing the product to the market. While offering significant advantages, the drying process is however energy intensive and costly. Both scenarios include drying of the protein product (to a DM (dry matter) content of 90 %), as the dried protein product is considered a more comparable substitute for imported soy, which has a long-shelf-life and can be supplied over longer distances.

One of the key challenges associated with the production of green protein is to establish synergies with other cascading uses of the biomass residues from the protein production process. There are evident synergies between protein production and biogas; while residues from the protein plant can be used as input to production of biogas, the biogas can be used to supply the process energy needed at the protein plant. In both scenarios, the production of protein is linked to biogas production, and the protein and biogas production plants are considered to jointly represent a biorefinery. In the large-scale scenario, a new biogas plant is established jointly with the protein plant, while in the small-scale scenario the protein plant is located next to an existing biogas plant, the capacity of which is expanded to accommodate the residue from the protein plant. In contrast to the protein plant, which operates only during the grass-growing season, the biogas plant operates the full year, with generation of biogas assumed to be constant throughout the year. Accordingly, for both scenarios investment in new biogas capacity is scaled so that annual processing capacity corresponds to the annual amount of residue, being stocked to ensure a constant daily supply of biomass input.

There are two types of residues resulting from protein production; a fibre fraction and a liquid fraction (juice). Both fractions can be used as input to biogas production, but there are also alternative uses, especially for the fibre fraction, which may be used for animal feed. Current biorefinery research is centred on identifying potential high value uses of the fibre fraction, e.g. production of insulation material, extraction of single-cell-protein or production of bioplastic (Morten Ambye-Jensen, personal communication April 2016). Yet, these potential alternative uses are still at an experimental stage, and it is therefore not possible to say which – if any – of the potential uses might be feasible in practice. The potential uses of the liquid residue fraction are limited, but it can be used directly on the field as fertilizer. However, in addition to the minerals that represent a fertilizer value, the juice contains a significant share of carbohydrates that is digested for biogas production, while maintaining the fertilizer value of the digestate from the biogas plant. In the small-scale scenario, the juice fraction is thus used for biogas production, while the fibre fraction is used for cattle feed at nearby farms. In the large-scale scenario, both the juice and fibre fraction is used for biogas production. This difference in use of residues is motivated by the differences in the case study areas. On Zealand, where livestock density is low, the commercial potential for the fibre fraction will be negligible, while the higher livestock densities in the Jutland case study makes it reasonable to expect demand for fibre for cattle feed.

In both scenarios, the biogas plant includes an on-site CHP (Combined Heat and Power) facility, where some of the biogas is used for producing heat and electricity required for processing at the biorefinery. In both scenarios, the biogas plant includes an up-grading unit, where biogas in excess of needs for processing is converted to gridded natural gas quality - biomethane. It is subsequently fed into the natural gas grid, where it substitutes fossil-based natural gas. Alternatively, the biogas could have been supplied to a local CHP, an option less flexible and lacking commercial potential due to few potential buyers. Moreover, the use of biogas for local CHP production frequently cause energy losses due to low demand for heat in the summer. Such loss is avoided with the up-grading option, as the natural gas grid serves as a storage facility, allowing greater flexibility to fit fluctuating energy demand. Considering these advantages of up-grading, combined with the fact that the natural gas infrastructure is well-developed in both case study areas, the up-grading option is considered the most advantageous use of biogas in both scenarios. The digestate from the biogas plant is used to substitute mineral fertilizer for arable crops in the vicinity of the biorefinery. For the small-scale scenario, the digestate is assumed to be applied to fields located in an average distance of 3 km from the biorefinery, while the average distance is 5 km for the large-scale scenario.

The land use and energy related substitutions as a consequence of shifting from the baseline scenario to the biorefinery scenarios cause several external impacts that are not internalised in current market prices. These include the changes in nitrogen leaching from changes in fertilizer applications associated with crop rotations, emission changes due to the substitution of natural gas with up-graded biogas, and emission changes due to changed demand for transport. These impacts are considered in the welfare economic analysis to the extent possible.

The analysis is bound to be associated with a significant degree of uncertainty due to the hypothetical nature of the scenarios. To address this, sensitivity analysis is conducted, exploring the significance of specific parameters.

In Table 2.1, the main characteristics of the two scenarios are summarised, and Figures 2.1 and 2.2 provide schematic representations of the two scenarios.

Table 2.1 Main characteristics of the scenarios analysed in the report.

	Large-scale scenario	Small-scale scenario
Processing capacity of protein plant (tonne DM per year)	150,000	20,000
Input	High yielding grass	High yielding grass
Protein product	Dried, substitutes soy	Dried, substitutes soy
Use of juice residue fraction	Biogas	Biogas
Use of fibre residue fraction	Biogas	Cattle feed
Biogas plant	New plant	Expansion of existing plant
Process energy	On-site CHP, biogas as fuel	On-site CHP, biogas as fuel
Use of excess biogas	Upgraded to natural gas quality	Upgraded to natural gas quality
Use of digestate	Fertilizer, substituting mineral fertilizer	Fertilizer, substituting mineral fertilizer

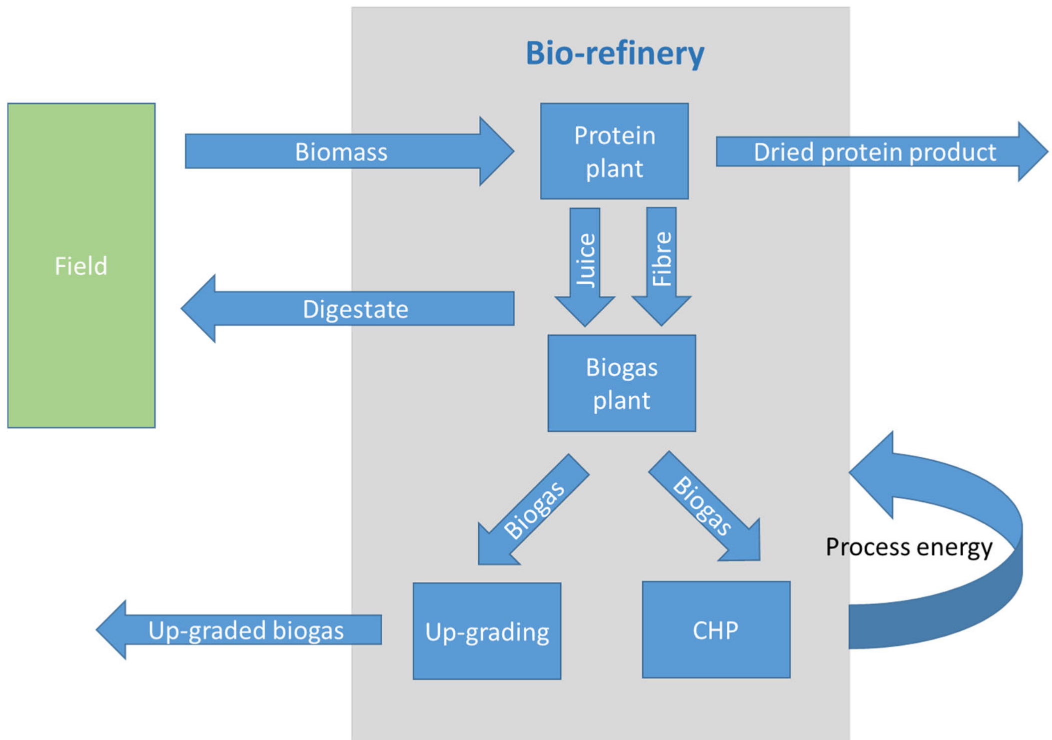


Figure 2.1 Schematic presentation of the large-scale scenario.

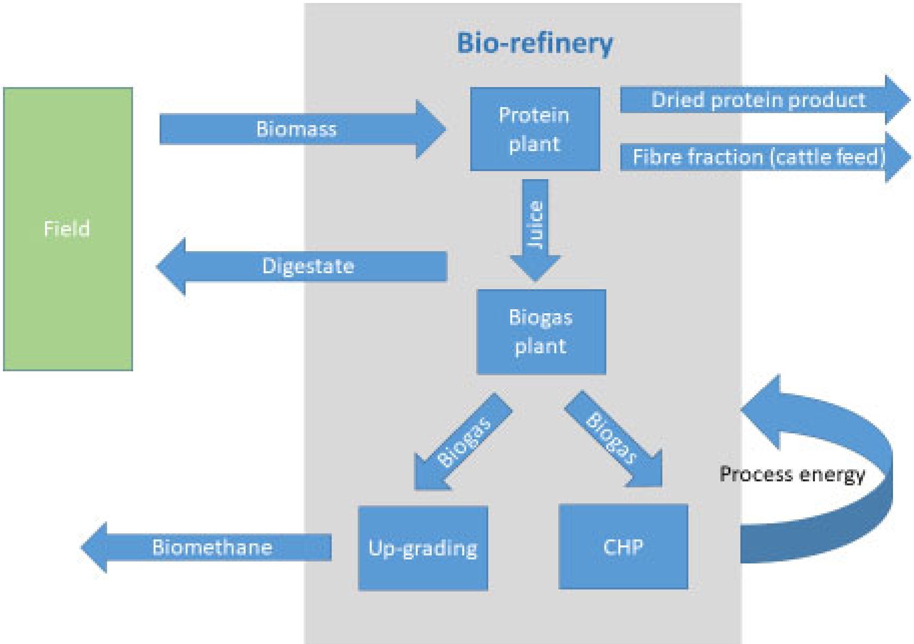


Figure 2.2 Schematic presentation of the small-scale scenario.

3 Biorefinery: Protein production

3.1 Input to and output from protein production

The protein production processes at the biorefinery are identical across the two scenarios. Hence, looking at the production of protein in isolation the only difference across the two scenarios is the scale of the production.

In both scenarios, the protein production is based on input of high yielding grass, cultivated in a five-year rotation, with four years of grass followed by one year with cereals. The dry-matter (DM) content of the grass is 18 %, implying that 1 tonne of fresh grass is equivalent to 0.18 tonne dry matter, or the other way around that 1 tonne dry matter is equivalent to the dry matter content of 5.6 tonnes of fresh grass. There are three outputs from the protein production process; 1) the protein product, 2) a fibre residue fraction, and 3) a liquid residue fraction (juice). There is a fixed production relationship between the input and different outputs; this assumed production relationship is specified in Table 3.1, which lists the DM % along with both the dry - and fresh weight of the input and outputs. The moisture content of the protein paste is 65.4 %, but is assumed to be further dried to 10 % moisture.

Table 3.1 Outputs from the processing of 1 tonne of grass (fresh weight). (Source: Sylvestre Njakou Djomo, 2018; see Annex 1).

Inputs	Weight (tonne)	Dry matter (DM) %	Dry weight (tonne)
Grass	1	18	0.18
Outputs	Weight (tonne)	Dry matter (DM) %	Dry weight (tonne)
Dried protein product (un-dried)	0.034 (0.088)	90 (34,6)	0.031 (0.031)
Liquid residue fraction (i.e. juice)	0.541	4.5	0.024
Fibre residue fraction	0.372	33.7	0.125
Sum – weight of outputs:	0.947 (1)		0.180

Based on the data in Table 3.1 and considering the DM processing capacities, the input and output quantities for the small and the large-scale protein production plants can be calculated; the results are shown in Table 3.2.

Table 3.2 Protein production: Annual inputs and outputs (tonne).

	Small-scale plant	Large-scale plant
Annual processing capacity (DM):	20,000	150,000
Annual grass input (fresh weight):	111,111	833,333
Protein product (dried to 90 % DM):	3,778	28,333
Fibre product (33.7 % DM):	41,333	310,000
Liquid residue (4.5 % DM; juice)	60,111	450,833

3.2 Changes in crop rotation induced by increased demand for grass

There will be changes in crop rotation as result of the increased demand for grass to extract green protein. Crop yields vary by a range of factors, including soil type and as a result, the land area required for producing the amount of grass needed as input for protein production is dependent on the soil types present in the case study areas, and the underlying assumptions regarding level of fertilization, type of grass etc. In order to account for differences in input and grass yield, grass production was evaluated across four soil types: coarse sandy soils, fine sandy soils, loamy soils and irrigated sandy soils. It was further assumed that grass was pure ryegrass (*Lolium perenne*) highly fertilized with nitrogen (450 kgN / ha). The estimated yield of biomass per ha was adapted from Hermansen et al. (2017), and the corresponding input of energy, other types of fertilizer than nitrogen and liming is based on Knudsen and Mogensen (Annex 4).

It is assumed that the production of grass displaces previous cereal production, specifically the production of winter wheat and spring barley, which in both case study areas are predominant cereal crops. In terms of acreage, these two crops jointly account for 75 – 80 % of cereal production in the case study areas.

The two case study areas are in fact fairly similar in terms of soil types and cereal production. Hence, in both areas there is an approximately even distribution of winter wheat and spring barley, and in terms of soil types, there is an approximately even distribution of arable land across three soil types (all without irrigation), namely JB 1 + 3 (sandy soils), JB 2 + 4 (fine sandy soils) and JB 5-8 (loamy soils).

In order to calculate the land area required to produce the necessary amount of grass in each scenario, it is necessary to calculate the average grass yield per hectare in the case areas. With reference to Table 3.3, the average annual yield per hectare for the highly fertilized and high yielding grass used as input to protein production ranges between 9,250 and 11,100 kg DM depending on the soil type. On average, the annual yield per hectare is 9,950 kg.

Table 3.3 Grass production in case areas.

Soil type	Share of land	Grass yield (kg DM/ha)
JB 1 + 3	0.333	9,250
JB 2 + 4	0.333	9,500
JB 5 - 8	0.333	11,100
Weighted average		9,950

Based on the average grass yield of 9,950 kg DM per hectare, combined with the annual processing capacities of the protein plants, the arable crop areas required for conversion to grass production can be calculated to 2,010 ha for the small-scale plant (20,000 tonnes DM / year) and 15,076 ha for the large-scale plant (150,000 tonnes DM / year). With reference to the approximately even distribution of winter wheat and spring barley for all three soil types, combined with the cereal yields for different soil types, the total displaced cereal production for the scenarios can subsequently be calculated. The area and yield information used to calculate the displaced cereal production for each of the scenarios is presented in Table 3.4. In the last two columns of Table 3.4 the displaced cereal production is quantified; the conversion from cereals to grass causes a total decrease in cereal production of 12,530 tonnes in the small-scale scenario and of 93,973 tonnes in the large-scale scenario.

The transition from cereals to grass triggers a decrease in the production of straw. In the baseline scenarios straw is collected and used for energy production at local district heating plants. Thus, the changes in land use could potentially have consequences for local energy production. In the small-scale scenario, the total annual decrease in straw production is 6,891 tonnes (3,800 tonnes straw from winter wheat and 3,091 tonnes from spring barley), while it amounts to 51,686 tonnes in the large-scale scenario (28,502 tonnes straw from winter wheat and 23,184 tonnes from spring barley). In comparison, total cereal straw production in Denmark is around 5,500,000 tonnes per year; of this 1,357,000 tonnes (approx. 24 %) is used for heat production, while between 28 and 35 % is used for bedding or feeding at farms (Birkmose et al., 2015). The remaining 40 – 48 % of total straw production is not utilised, indicating a significant surplus production of straw. Based on this, it seems reasonable to assume, that energy production will be unaffected by the decrease in straw availability, as the significant surplus production suggests that it will be fairly unproblematic to find new suppliers of straw. Accordingly, the analysis does not consider changes in energy production induced by reduced production of straw in the biorefinery scenarios.

Table 3.4 Displaced cereal production (Knudsen and Mogensen, cf. annex 4).

Cereal crop	Soil type	Share of area	Small-scale scenario - No. of hectares	Large-scale scenario - No. of hectares	Yield per hectare (kg)	Small-scale scenario - Displaced cereal production (tonne)	Large-scale scenario - Displaced cereal production (tonne)
Winter wheat	JB 1 + 3	0.167	335	2,513	5,250	1,759	13,191
	JB 2 + 4	0.167	335	2,513	6,600	2,211	16,583
	JB 5 - 8	0.167	335	2,513	8,775	2,940	22,048
Total Winter wheat						*6,910*	*51,822*
Spring barley	JB 1 + 3	0.167	335	2,513	4,600	1,541	11,558
	JB 2 + 4	0.167	335	2,513	5,351	1,793	13,445
	JB 5 - 8	0.167	335	2,513	6,825	2,286	17,148
Total Spring barley						*5,620*	*42,151*
Total			2,010	15,076		12,530	93,974

3.3 Energy and labour

In addition to grass, the production of protein also requires inputs of energy and labour. Njakou Djomo (2018) calculates the heat and electricity consumption associated with the processing of 1 tonne of grass (see Annex 1). Around 55 % of the electricity is used for pressing, while 38.8 % is used for drying; the remaining 6.7 % is used for skimming and dehydration. The heat is solely used for protein coagulation. Using the estimates from Njakou Djomo (2018) the total demand for electricity and heat for running the protein plant in each of the scenarios is quantified in Table 3.5. The energy used for processing at the protein plant is supplied by the onsite CHP, implying that the energy use does not entail direct expenses; instead it represents an indirect costs as it reduces the amount of biogas available for sale. The indirect costs of energy used for processing will be assessed jointly for the entire biorefinery in the following chapter.

Table 3.5 Energy used for processing at the protein plant (cf. flow diagrams in Annex 1).

	Grass input (tonne)	Heat (MJ/tonne)[1]	Electricity (kWh/tonne)[1]	Total heat consumption (MJ)[1]	Total electricity consumption (kWh)
Small-scale scenario	111,111	28.64	5.57	3,182,219	618,888
Large-scale scenario	833,333	28.64	5.57	23,866,657	4,641,665

[1] Based on Njakou Djomo (2018).

In terms of labour use, there are limited experiences from which to estimate demand. Accordingly, any estimate of the demand for labour is bound to be associated with significant uncertainty. The estimation of labour demand for the small-scale plant is based on input from Morten Ambye-Jensen (personal communication November 2018). Since extraction of protein relies on the input of fresh grass it implies that processing is confined to the grass harvesting season from May to October. This in turn implies that the production plants stand idle in the remaining six months, and to maximise the rate of return on the capital invested it is important that the processing capacity is used in full during the productive period. It is assumed that the protein plant will be running 3,000 hours per year, corresponding to running day and night, five days a week during the productive season. Moreover, it is assumed that the plant needs to be staffed day and night. Based on experience from the pilot plant it is suggested that the small-scale plant is to be staffed with two persons at all times during the productive period; the employees will make turns in three-shift working. With 3,000 operating hours / year and two persons present at all times, total labour demand for the small-scale plant is 6,000 hours. Using a salary rate of 300 DKK / hour (Fog and Thierry, 2016), total labour expenses for the small-scale plant amounts to 1,800,000 DKK per year.

The processing capacity of the large-scale plant is 7.5 times higher than that of the small-scale plant. Due to economies of scale the demand for labour is expected to be relatively lower. Assuming twice the efficiency the number of persons per shift can be calculated to 7.5, which is rounded up to eight persons. With 3,000 hours / year total labour demand for the large-scale plant becomes 24,000 hours, which using the salary rate of 300 DKK / hour is equivalent to a total expense of 7,200,000 DKK per year.

There are a few things, which should be noted, in relation to the calculated labour demand. During the six months, where the plant stands idle, there will be no or at least very limited demand for labour, except perhaps for some maintenance work. This seasonality in labour demand may be problematic, particularly if the demand is for skilled labour. Hence, it might be difficult to attract employees if employment is offered only for 6 out of 12 months, and it may become difficult to ensure continuity in the labour force, which may be an important parameter in terms of running the plant efficiently. One way of addressing the problem may be to offer slightly higher salaries in order to make the protein plant an attractive place of employment. Another relevant option could be to expand the perspective to the entire biorefinery rather than restricting the focus to the protein part of the refinery. Hence, in terms of labour there may be important synergies between the protein plant and the biogas plant; and assessing labour demand at the aggregate refinery level rather assessing it separately for the two types of production plants, it may be possible to reduce the total number of employees. Thus, through careful planning of the work, where operation of the protein plant is prioritised labourwise during the harvesting season while maintenance work is scheduled to take place during the non-harvest season, it may be possible to address issues associated with the seasonality of protein production. Finally, the possibilities of entering into some kind of labour-force sharing schemes with other local businesses, e.g. district heating plants, whose production is also seasonal (with the opposite seasonal pattern as the protein plant) could also be considered. Although it could have implications for the efficiency of plant operations. The potential issues related to the seasonality of plant operations will not be further considered here.

Estimation of labour demand is restricted to needs for the actual operation of the plant, with a salary rate reflecting the average for skilled workers such as e.g. smiths or electricians. However, it may also be necessary to have a plant manager and / or managing director (especially at the large-scale plant), and this may add to total personnel costs. It is assumed that there are synergies between the protein and biogas operations, with a joint management staff for the biorefinery, and the costs for this is included in the estimation of personnel costs for the biogas plant (see Chapter 4).

3.4 Transport of grass to biorefinery – distances and costs

In relation to calculation of the demand for transport of biomass to the biorefinery, it is assumed that the average transport distance in the large-scale scenario is 10 km, while it is 5 km in the small-scale scenario. To keep transportation costs as low as possible, it is desirable to minimize the distances over which the biomass has to be transported. The distances in the two scenarios have been determined as follows. In both case areas, approximately 65 % of the total land area is classified as agricultural land; of this approximately 68 % is used for cereal production in the Zealand case study area while the corresponding share in the Jutland case study area is approximately 40 %. The focus on land used for cereal production follows from the assumption that the land used for grass production has previously been used for the production of cereals. Two limitations are imposed in terms of how large a share of the cereal area that can be converted. One limitation is that there has to be at least 20 % cereals left in the crop rotations in the protein production scenarios; this limitation is imposed in order to ensure that grass fields can be converted at four-year intervals. The other limitation is that a maximum of 40 % of agricultural land can be converted. Based on the share of agricultural land in the case study areas, and the respective shares of agricultural land used for cereal production, and considering the imposed limitations, the size of the catchment areas for the two scenarios can be calculated to 96.6 km^2 for the small-scale plant and 579.8 km^2 for the large-scale plant. For the Jutland case, where cereal production does not represent the predominant agricultural crop, it is the limitation that maximum 80 % of cereal areas can be converted that represents a binding constraint. In contrast, the binding constraint in the Zealand case, where cereal production represents the predominant crop, is the 40 % limit. Assuming that the biorefineries are located at the center of the catchments, and that the catchments are shaped as perfect circles, the mean distances for the two scenarios can subsequently be calculated to 9 km for the large-scale scenario, and to 3.7 km for the small-scale scenario[2]. Rounding these average distances, we arrive at the assumed distances of 10 and 5 km for the two scenarios. It may be noted that these distances are estimated as the crow flies, thereby not reflecting the fact that most roads do not represent straight lines. This may imply that the distances used here underestimates the distances applying in reality. However, the fact that the numbers are rounded upwards work in the other direction.

As it is important that the grass is processed immediately after harvest, and as the necessary preprocessing of the grass (shredding) ideally is integrated as part of the harvesting procedure, the harvesting, preprocessing and transport of the grass is modelled jointly. The costs associated with transport of grass to the biorefinery have been estimated by Claus Grøn Sørensen (personal communication 2017). Costs vary depending on the yield per hectare and the transport distance as shown in Table 3.6. There are quite small differences in costs per kgDM between the distances of the two scenario plants

[2] Mean distance calculated based on formula from: http://mathforum.org/library/drmath/view/62529.html.

due to the modest share of transportation costs (22-33 %) relative to the distance independent harvesting costs (67-78 %).

Table 3.6 Harvesting and transport costs for highly fertilized grass; DKK/kg DM.

	Soil type		
	Sandy soils (JB 1+3)	Fine sandy soils (JB 2+4)	Loamy soils (JB 5-6 & JB 7-9)
Yield (kg DM/ha)	9,250	9,500	11,100
Distance			
5 km	0.35	0.35	0.34
10 km	0.38	0.37	0,36

Based on the data in Table 3.6, combined with the land area required for grass production and its soil types (see Table 3.3), the harvesting and transportation costs for each of the scenarios can be calculated to 346 DKK / tonne DM for the small-scale scenario and 369 DKK / tonne DM for the large-scale scenario; see Table 3.7. With a DM content of 18 % this is equivalent to 62 and 66 DKK / tonne fresh grass.

Table 3.7 Aggregate harvesting and transportation costs for the two scenarios.

		Small-scale scenario	Large-scale scenario
Total area used for grass production (ha), of which:		2,010	15,076
Annual DM input (tonne):		20,000	150,000
Average distance (km):		5	10
Sandy soils (JB 1+3)	Ha:	670	5,025
	Yield per ha (kg DM/ha):	9,250	9,250
	Cost (DKK/kg DM):	0.35	0.38
	Total costs (DKK):	2,169,125	17,664,047
Fine sandy soils (JB 2+4), ha:	Ha:	670	5,025
	Yield per ha (kg DM/ha):	9,500	9,500
	Cost (DKK/kg DM):	0.35	0.37
	Total costs (DKK):	2,227,750	17,664,047
Loamy soils (JB 5-6 & JB 7-9)	Ha:	670	5,025
	Yield per ha (kg DM/ha):	11,100	11,100
	Cost (DKK/kg DM):	0.34	0.36
	Total costs (DKK):	2,528,580	20,081,232
Total costs (DKK):		6,925,455	55,409,325
Average costs (DKK/tonne DM):		346	369

3.5 Investment, operation and maintenance

Each of the scenarios includes the construction of a new protein production plant with annual processing capacities of 20,000 and 150,000 tonnes DM respectively. The estimated investment and maintenance costs for the small-scale plant are based on experiences from the pilot plant, taking into account potential economies of scale (Ambye-Jensen, November 2017). Subsequently, the investment costs for the large-scale plant is estimated by up-scaling the estimate for the small-scale plant based on the difference in processing capacities between the two plants, while also adjusting for economies of scale by reducing costs by 20 %. In this connection, it may be noted that Danish Energy Agency (2017) presents an economy of scale equation, which can be used to calculate investment costs for a plant with a given capacity based on the investment costs for an in technical terms similar plant, with a different capacity. The equation includes a proportionality factor, which usually is set to somewhere between 0.6 and 0.7, although it is noted that extended project schedules may cause it to increase, just as it is equal to 1 if dealing with modular projects. The difference between the capacities of the protein plants in the small and the large-scale scenarios considered here are believed to fall within the category of extended project schedules, implying that the relevant proportionality factor is probably higher than 0.6-0.7. The total investment for the small-scale plant is 25 mDKK, and the investment for the large-scale plant is set to 150 mDKK (see Table 3.8). Referring to the scale equation from Danish Energy Agency (2017:16) this corresponds to using a scaling factor of 0.9 in the scaling of costs between scenarios, to reflect that relative costs are expected to decrease with increasing scale, at least to a certain extent.

The estimated investment and maintenance costs for the two scenarios, along with the assumptions underlying the estimates, are presented in Table 3.8, where it is seen that on an annual basis investment and maintenance costs are estimated to be 187 DKK / year / tonne DM for the small-scale plant and 150 DKK / year / tonne DM for the large-scale plant. The lifetime is assumed to be 15 years for both plants, and annual maintenance costs as a percent of the investment is 4 %. The annualizing is based on an interest rate of 7 %.

Table 3.8 Protein plant: Investment and maintenance costs.

	Small-scale plant	Large-scale plant
Interest rate (%)	7	7
Investment lifetime	15	15
Maintenance (% of investment costs)	4	4
Processing capacity (tonne DM/year)	20,000	150,000
Investment costs (mDKK)	25	150
Investment costs (DKK/tonne DM)	1,250	1,000
Annualized investment costs (mDKK/year)	2.7	16.5
Annualized investment costs (mDKK/year/tonne DM)	137	110
Maintenance costs (mDKK/year)	1	6
Maintenance costs annualized (DKK/year/tonne DM)	50	40
Total annualized investment and maintenance costs (mDKK/year)	3.7	22.5
Total annualized investment and maintenance costs (DKK/year/tonne DM)	187	150

3.6 Input costs – grass

A simple market price approach for assessing the grass input costs cannot be used in the present case, as it reflects the price of grass harvested and removed. In the present scenarios, harvesting and transport is considered an integrated part of the biorefinery operations, implying that the biorefinery will purchase on-field grass from farmers. Hence, the biorefinery must shoulder harvest and transport expenses. This division of work requires adjustment of the market price of grass biorefinery.

Moreover, farmers cannot be expected to convert from cereal production to grass production unless they have an economic incentive to do so, and thus must be compensated for any decrease in the contribution margin (CM) caused by the substitution of cereal production with grass production. As a minimum, the farmer's profit should not decrease when shifting from baseline to biorefinery scenarios.

The minimum compensation can be estimated as the lost CM from cereal production plus the costs associated with establishing and fertilising the grass fields. Table 3.9 shows CMs for cereal production in the baseline along with the costs associated with producing grass in the biorefinery scenarios. The calculated CMs and cultivation costs[3] are based on FarmtalOnline (www.farmtalonline.dk), adjusted to reflect the yields and fertilizer use associated with the analyzed scenarios (See Annex 4). Yield and fertilizer use data represents averages over several years, hence reflecting the variability in yields and fertilizer use.

It follows from Table 3.9, that CM for Spring barley as well as Winter wheat grown on sandy soils is negative. This seems counterintuitive, as a negative CM would render it profitable to leave the land idle, rather than to grow cereals. However, farmers receive an EU subsidy for cultivating their land, securing a positive CM, even if of limited magnitude. The reason why the subsidy is not included here, is that the aim is to identify the difference between the baseline scenario and the biorefinery scenarios. As the subsidy will be granted in all circumstances, it is not necessary to include it here.

Table 3.9 Contribution margins for cereal production and the costs of producing grass (year: 2017).

		Small-scale scenario			Large-scale scenario		
		Spring barley	Winter wheat	Grass	Spring barley	Winter wheat	Grass
Sandy soils (JB 1+3)	Ha:	335	335	670	2,513	2,513	5,026
	CM (DKK/ha):	-683	-601		-683	-601	
	Cultivation cost, excl. harvest + transport (DKK/ha)			-5,628			-5,628
	Cost (DKK/year):	228,805	201,335	-3,770,760	1,716,379	1,510,313	-28,286,328
Fine sandy soils (JB 2+4)	Ha:	335	335	670	2,513	2,513	5,026
	CM (DKK/ha):	203	1,008		203	1,008	
	Cultivation cost, excl. harvest + transport (DKK/ha)			-5628			-5,628
	Cost (DKK/year):	-68,005	-337,680	-3,770,760	-510,139	-2,533,104	-28,286,328
Loamy soils (JB 5-6 & JB 7-9)	Ha:	335	335	670	2,513	2,513	5,026
	CM (DKK/ha):	1,476	2,922		1,476	2,922	
	Cultivation cost, excl. harvest + transport (DKK/ha)			-5,654			-5,654
	Cost (DKK/year):	-494,460	-978,870	-3,788,180	-3,709,188	-7,342,986	-28,417,004
Sum - CM loss + grass cultivation costs (DKK/year)			-12,778,575			-95,858,385	
Average cost scenario (DKK/ha):			-6,358			-6,358	
Average cost scenario (DKK/tonne DM):			-639			-639	
Average cost (DKK/Feed unit):			-0.75			-0.75	

It follows from Table 3.9 that the minimum compensation demanded by farmers on average is 6,358 DKK / ha, which is equivalent to 639 DKK / tonne DM. Thus, this is the minimum price, which the biorefinery must be expected to

[3] Cultivation costs include expenses for seeds and fertilizers (N, P and K) as well as machine and labor costs for sowing and applying fertilizer. More than 50 % of the estimated cultivation costs can be attributed to the purchase of N fertilizer (450 kg / ha; 7.4 DKK / kg).

pay farmers for the grass. In addition to this comes the costs, which the biorefinery must pay for harvesting the grass and transporting it to the biorefinery. With reference to Table 3.7, these costs were estimated to 346 DKK / tonne DM for the small-scale scenario and 369 DKK / tonne DM for the large-scale scenario. In total, the resulting input cost for grass is 985 and 1,008 DKK / tonne DM for the small and large plants respectively. Recalculated into a price per feed unit, this is equivalent to 1.16 (small-scale) and 1.29 (large-scale) DKK / feed unit, which is very close to the price of 1.19 DKK / feed unit reported in FarmtalOnline for 2017.

3.7 Value of outputs

The three outputs from the protein plant are the protein product, a liquid residue fraction (juice) and a fibre residue fraction. In both scenarios, the juice fraction is used as input to biogas production, whereby it stays within the boundaries of the biorefinery. The economic value, which the juice represents is not redeemed as such, and is not accounted for directly in the analysis. Instead, it is accounted for indirectly, through the value of the biogas, which is produced also with juice input.

How the fibre fraction is used differs between the two scenarios. In the large-scale scenario where the fibre fraction is used for biogas, the value of the fibre is included indirectly – as for the juice – through the value of the produced biogas. For the small-scale scenario, where the fibre is used for cattle feed, its value is accounted for based on the price of ensiled grass; the feed that the fibre fraction is assumed to substitute. Based on John Hermansen (personal communication 2018) the feeding value of the fibre fraction is 0.83 feed units / kg DM. It follows from tables 3.1 and 3.2 that the DM content of the fibre fraction is 33.7 %, and that a total of 41,333 tonnes fibre is produced at the small-scale plant. Hence, the total feed value of the fibre fraction can be calculated to 11,561,347 feed units. With a price per feed unit of 1.19 DKK (FarmtalOnline[4]), the annual value of the fibre fraction can subsequently be calculated to 13.7 mDKK, corresponding to 688 DKK / tonne DM biorefinery input. It should be noted that this value does not take account of potential transportation costs associated with transporting the fibre from the biorefinery to the farms where it is to be used for feed. Hence, the extent to which this value can be redeemed depends on the extent to which it is possible to find cattle farmers who are willing to purchase the fibre, and on the price, they are willing to pay. Preferably, it should be farmers located in the immediate vicinity of the protein plant in order to minimize transportation costs. The substitution of ensiled grass with fibre may trigger further changes in land-use not considered in the present analysis. It should however be noted that the substitution, due to a reduced demand for grass silage in the biorefinery scenario, potentially could lead to a conversion from grass to cereal production on fields used for silage production in the baseline scenario. Should this be the case, there will not necessarily be a net increase in the area used for grass production when moving from the baseline to the biorefinery scenario. Instead, land use impacts will simply involve a relocation of areas grown with grass and cereals spectively.

The protein product will be supplied to the market in both scenarios, at a price expected to correspond to the price of soy meal, its nearest substitute. The substitution relationship between the protein product and soymeal is determined based on their protein contents. According to SEGES (2017) the protein content of soy meal (husked and toasted) is 45.8 %; i.e. one tonne of soy meal contains 458 kg protein. The protein product, on the other hand, has a DM content of 90 %, and based on Hermansen et al. (2017) its protein is assumed to account for 47 % of the DM content. Accordingly, 1 tonne of grass based protein product contains 423 kg protein (1 tonne * 0.9 tonne DM / tonne * 0.47 tonne protein / tonne DM). On this basis, 1.083 tonnes green protein is required to substitute 1 tonne of soymeal. The average price of soymeal was 271 DKK / hkg in 2016 (Statistikbanken, 2018), and taking into account the substitution relationship, the price for 1 tonne of protein product can be calculated to 2,502 DKK ((271 DKK / hkg * 10 hkg / tonne) / 1.083). Subsequently, with reference to the produced amounts of green protein for the two scenarios listed in Table 3.2, the value of the produced protein can be estimated. For the small-scale plant the value of the protein product is 9.5 mDKK / year, and for the large-scale plant the value is 70.9 mDKK / year. Converting these values into a revenue per tonne grass input, each tonne of DM input is expected to generate a revenue from the sale of protein product equal to 473 DKK in both scenarios.

Table 3.10 lists the different expenditure and income components identified above.

Table 3.10 Overview of costs and revenues related to the protein plant of the biorefinery.

	Small-scale plant		Large-scale plant	
Annual DM input (tonne):	20,000		150,000	
	Total (DKK/year)	Per tonne DM input (DKK/tonne DM)	Total (DKK)	Per tonne DM input (DKK/tonne DM)
Costs				
Grass - compensation to farmers	12,778,575	639	95,858,385	639
Grass – harvesting and transport	6,925,455	346	55,409,325	369
Labour	1,800,000	90	7,200,000	48
Energy	-	0	-	0
Investment	2,744,866	137	16,469,194	110
Maintenance	1,000,000	50	6,000,000	40
Total costs	*25,248,896*	*1,262*	*180,936,904*	*1,206*
Revenues				
Residue juice	-	0	-	0
Fibre fraction	13,758,003	688		
Protein product	9,455,415	473	70,915,611	473
Total revenues	*23,213,417*	*1,161*	*70,915,611*	*473*

4 Biorefinery: Biogas production

4.1 Inputs to and outputs from biogas production and upgrading

In the large-scale scenario both the liquid and the fibre residue fractions from the production of protein is used for biogas production, while in the small-scale scenario it is only the liquid fraction. This implies that the amount of biogas produced per tonne grass input to the biorefinery differs in the two scenarios. The biogas production per tonne of grass input in each of the two scenarios is presented in Table 4.1, where assumptions for the calculations of biogas yield are listed too. Due to leakages at biogas plants, actual yield is less than the theoretical yield. Table 4.1 lists as well the theoretical gross biogas yield as the loss-adjusted yield. According to the Danish Energy Agency (Energistyrelsen, 2016) the average methane loss from leakages was 2.2 % in 2015, and a reduction to 1.8 % is expected for 2020, with a further improvement to 1.0 % by 2030. These yield losses refer to averages of both new and old plants, and the methane loss rate relevant for the present analysis is set to 1% of gross production.

It follows from Table 4.1 that biogas production per tonne of grass input is about five times higher when both fibre and juice is used for biogas, than when only juice is used. It should be noted, that biogas production per tonne VS (Volatile Solids) (and thereby also per tonne DM, as the VS / DM relationship is the same for the two types of biomass) is higher for the juice than for the fibre fraction. The DM content of juice plus fibre is 16.4 %, which is quite high compared to the conventional DM observed. As a rule of thumb, the maximum DM content of input, which biogas plants can handle using conventional technologies, is about 15 % (Henrik B. Møller, personal communication April 2016). Still, with 16.4 % fairly close to this guiding maximum we assume that conventional technologies can be used in both scenarios.

Table 4.1 Biogas production per tonne grass input to biorefinery.

	Juice	Fibre	Juice + fibre
tonne/tonne grass	0.541	0.372	0.913
DM %	4.5	33.7	16.4
DM (tonne)	0.024	0.125	0.150
VS/DM	0.9	0.9	0.9
Biogas potential (55 % CH_4), m^3/tonne VS	541.67	411.67	432.81
Biogas yield (55 % CH_4), m^3/tonne grass[1]	11.87	46.45	58.32
Biogas, loss adjusted yield[2] (55 % CH_4), m^3/tonne grass	11.75	45.98	57.73

[1] Gross biogas yield. Gross biogas yield (m^3/tonne grass) = (tonne/tonne grass)*(DM%/100)*VS/DM*Biogas potential (m^3/tonne VS).

[2] Loss adjusted biogas yield = gross biogas yield * (100-1).

Based on the loss adjusted biogas yields per tonne input in Table 4.1 combined with the amount of juice and fibre produced at the protein plant in each of the scenarios (Table 3.2), total biogas production can be calculated as shown in Table 4.2. Table 4.2 also contains information on the amount of digestate produced in each of the scenarios, and the DM content of the digestate, which is seen to be 2.1 % in the small-scale scenario and 10 % in the large-scale scenario. In both scenarios, the digestate is used as fertilizer on nearby fields, where it substitutes the use of mineral fertilizer. The biogas production indicated in

Table 4.2 is the gross biogas production obtained in each scenario; of which a share is retained for an on-site CHP facility producing the heat and electricity required for processing at the entire biorefinery. The remaining share, i.e. the net production, is upgraded (also at an on-site facility) to natural gas quality and supplied to the grid.

Table 4.2 Biogas production: Inputs and outputs.

	Small-scale scenario	Large-scale scenario
DM input to biorefinery (tonne DM)	20,000	150,000
Grass input to biorefinery (tonne, fresh weight)	111,111	833,333
Input to biogas production (tonne, fresh weight)		
Juice	60,111	450,833
Fibre	0	310,000
Total	60,111	760,833
Biogas loss adjusted yield (55 % CH_4; m^3)		
From juice	1,305,509	9,791,315
From fibre	-	38,319,384
Total	1,305,509	48,110,699
Biogas (55 % CH_4) per tonne grass input (m^3/tonne, fresh weight)	11.75	57.73
Biogas (55 % CH_4) per tonne DM grass input (m^3/tonne DM)	65.28	320.74
Digestate per tonne grass input to biorefinery (tonne/tonne, fresh weight)	0.526	0.846
Digestate total (tonne, fresh weight)	58,444	705,000
DM % (Digestate)	2.1	10
Total DM in digestate (tonne DM)	1,227	70,500

When biogas is upgraded, CO_2 (carbon dioxide) and H_2S (hydrogen sulfide) along with other compounds are removed from the biogas, leading to an increased concentration of CH_4 (methane), which increases its heating value. There are several different methods for upgrading biogas to natural gas quality. The most commonly used of these are Water scrubbers, Pressure Swing Adsorption and Amin scrubber (chemical absorption) (Energistyrelsen, 2014). The energy requirements as well as the investment costs and methane losses are of the same magnitude across the three technologies, although there are minor differences in e.g. the composition of energy use (the Amin scrubber uses both heat and electricity while the other two technologies only use electricity) (Energistyrelsen, 2014). In the scenarios analysed here, upgrading is assumed to be with the pressure swing adsorption approach; which is not expected to influence results compared to if another upgrading technology had been chosen.

4.2 Energy

Table 4.3 and 4.4 shows the energy requirements for processing at the biogas plant and for operating the upgrading unit. Energy use at the biogas plant is specified per tonne of grass input, and total use for each scenario is also specified. Moreover, the energy use per tonne treated biomass is also calculated. The energy required for upgrading is specified per tonne grass input (both fresh weight and DM weight), and total electricity demand for both scenarios is also specified. The significant differences in electricity use per unit of input is caused by the differences between the scenarios in terms of what is used as input to biogas production, and is hence not caused by differences in technology.

Table 4.3 Energy used for processing at the biogas plant (cf. flow charts in Annex 1).

	Small-scale scenario (Juice only)	Large-scale scenario (Juice & fibre)
Grass input (tonne)	111,111	833,333
Biomass to biogas (tonne, fresh weight)	60,111	760,833
Heat (MJ/tonne grass input to biorefinery)	16.23	79.64
Electricity (kWh/tonne grass input to biorefinery)	3.15	15.49
Total heat consumption (MJ)	1,803,333	66,366,667
Total electricity consumption (kWh)	350,000	12,908,333
Heat (MJ/tonne DM grass)	90.17	442.44
Electricity (kWh/tonne DM grass)	17.50	86.06
Heat (MJ/tonne biomass)	30.00	87.23
Electricity (kWh/tonne biomass)	5.82	16.97

Table 4.4 Energy use at upgrading facility (cf. flow charts in Annex 1).

	Grass input (tonne)	Electricity (kWh/tonne grass input to biorefinery)	Total electricity consumption (kWh)	Electricity (kWh/tonne DM grass)
Small-scale scenario	111,111	1.54	171,111	8.56
Large-scale scenario	833,333	9.95	8,291,663	55.28

4.3 Labour

Demand for labour to run the biogas plant is expected to be fairly constant over the year, with production running continuously. While the input for biogas production is produced during the six summer months, it is assumed that this biomass is stored so that biogas production will be more or less constant over the year. This goes for both the small and the large-scale scenario.

4.3.1 Labour demand in large-scale scenario

Maabjerg Energy Center – Biogas A/S is one of the largest biogas plants currently in operation in Denmark. The plant has an annual processing capacity of 800,000 tonnes (Energistyrelsen, 2014), which corresponds to the size of the plant in our large-scale scenario (760,833 tonnes cf. Table 4.3). The annual biogas production of Maabjerg Energy Center is around 20 million m^3 [5], which is less than half the production in our large-scale scenario. Thus, while the Maabjerg Energy Center biogas plant is similar in terms of processing capacity, there are significant differences between the two when it comes to biogas production. However, in terms of labour demand, processing capacity is assumed to be a more decisive factor than biogas production, and labour use at Maabjerg Energy Center - Biogasis considered to represent a relevant yardstick for labour demand at the biogas plant in the large-scale biorefinery scenario. In the annual report from Maabjerg Energy Center – Biogas total personnel expenses (including salaries, pension payments and others) for 2016 are reported to have been 5,839,000 DKK, based on an average number of full-time employees of 11 persons. The staff includes a managing director, a plant manager, a transport manager, a clerk, a laboratory technician, four smiths and two electricians.[6] In comparison, personnel expenses were

[5] See annual report of Maabjerg Energy Center biogas: https://www.maabjergenergycenter.dk/media/1515/mec_biogas_aarsrapport_2016.pdf

[6] https://www.maabjergenergycenter.dk/om-biogas/organisation

5,492,000 million DKK in 2015. Staff does not include lorry drivers, which is subcontracted. Thus, total annual labour costs for the large-scale plant are assumed to be around 5.8 million DKK, corresponding to unit costs as indicated in Table 4.5. The corresponding average annual salary for each of the 11 employees is 530,000 DKK, which can be converted into an average hourly rate of approximately 330 DKK (assuming 1,600 working hours per year). This salary rate is slightly higher than the rate of labour costs at the protein plant (Section 3.3), due to the biogas plant including non-technicians, e.g. managing director and plant manager.

Table 4.5 Labour costs for large-scale biogas plant.

	Cost
Total labour costs (MDKK)	5.8
DKK/tonne grass input	6.96
DKK/tonne DM Input	38.67
DKK/tonne input to biogas	7.62
DKK/m^3 gross biogas production	0.12

As mentioned previously (Section 3.3) there are expectations for labour-synergies between the protein and biogas plants through joint management. Whether it is reasonable to assume that management of the grass refinery can be added to the tasks associated with managing the biogas plant without increasing the number of staff can be questioned, and labour costs for the biorefinery may hence represent a conservative estimate.

A benchmarking analysis of biogas plants (Hjort-Gregersen, 2015) reports personnel expenses in the range of 12-25 DKK / tonne. The high degree of variability in the estimates from Hjort-Gregersen (2015) is caused in part by not accounting for subcontracting (e.g. of transport). In Jacobsen et al. (2013), the average labour costs are reported to be between 5 and 7 DKK per tonne, which corresponds well with the labour cost estimates used in the present analysis, c.f. Table 4.5.

4.3.2 Labour demand in small-scale scenario

In the small-scale scenario, the production of biogas with juice residue is assumed to take place at an existing plant, where the capacity can accommodate the residues from protein production. Assuming that the expansion mainly requires additional reactor capacity, the demand for more labour is limited. Møller and Martinsen (2013) reported a biogas plant with a daily biomass input of 50 tonnes, with annual labour demand of 365 hours / year. The capacity required for the small-scale scenario is roughly three times the capacity of the plant in Møller and Martinsen (2013), and scaling the demand for labour we infer an estimated demand for labour of 1,000 hours / year. With an hourly rate of 300 DKK the labour costs related to the expanded production of biogas in the small-scale scenario amounts to a total of 300,000 DKK, corresponding to unit costs as shown in Table 4.6.

Table 4.6 Labour costs associated with biogas production in small-scale scenario.

	Cost
Total labour costs (DKK)	300,000
DKK/tonne grass input	2.70
DKK/tonne DM Input	15.00
DKK/tonne input to biogas	4.99
DKK/m^3 gross biogas production	0.23

Contrasting the unit labour costs estimates for biogas production in the large and small-scale scenarios (see tables 4.5 and 4.6) it is clear that labour costs *per tonne input* are lower in the small-scale scenario, whereas when it comes to costs *per m^3 produced biogas* they are less in the large-scale scenario. This difference in relative costs is caused by the fact that labour costs per unit input is significantly lower when not establishing new plant; however biogas production per tonne input is significantly lower in the small-scale scenario where the liquid residue fraction constitutes the sole input to biogas production.

4.4 Gross biogas production and upgraded gas for sale

With reference to sections 3.3 and 4.2 the total demand for energy for processing at the biorefinery can now be calculated as specified in Table 4.7, and from this can be calculated how much of gross biogas production is required to produce the energy needed for processing.

Table 4.7 Aggregate demand for process energy at biorefinery.

	Small-scale scenario		Large-scale scenario	
	Heat (MJ)	Electricity (kWh)	Heat (MJ)	Electricity (kWh)
Protein plant	3,182,219	618,888	23,866,657	4,641,665
Biogas plant	1,803,333	350,000	66,366,667	12,908,333
Upgrading	0	171,111	0	8,291,663
Total	4,985,552	1,139,999	90,233,324	25,841,661
Per tonne grass input	44.9	10.3	108.3	31.0
Per tonne DM input	249.3	57.0	601.6	172.3

The on-site CHP producing the heat and electricity needed for processing is assumed to have an overall energy efficiency of 85 %, with heat and electricity produced in a fixed relationship. The power efficiency of the CHP is set to 35 % while the thermal efficiency is set to 50 %. Using these assumptions, Njakou Djomo (2018) calculate that 5.3 m^3 biogas / tonne grass input is needed to cover the demand for electricity and heat for processing in the small-scale scenario, while the corresponding amount for the large-scale scenario is 16.1 m^3 biogas / tonne grass input. Comparing these figures with the gross biogas production (11.75 and 57.73 m^3 biogas / tonne grass input, respectively, cf. Table 4.1) the internal energy demand is seen to consume 45 % and 28 % of gross biogas production in the small-scale and large-scale scenarios respectively. This difference is mainly caused by differences relating to biogas production and the use of fibres, whereas energy use per unit of input at the protein plant is the same for both scenarios. Based on Njakou Djomo (2018) heat and electricity production per unit input at the on-site CHP's are presented in Table 4.8. It follows from Table 4.8 that the amount of electricity produced at the on-site CHP exactly matches the amount needed for processing at the biorefinery in both scenarios; hence, for electricity there is no surplus production (cf. the last two rows). For heat, on the other hand, there is a surplus production arising due to the assumed relationship between heat and electricity. The surplus heat production is considered lost, as supplying it to local district heating grids is not regarded to be a viable option. The situation would have been different had the surplus energy production instead been in the form of electricity, as it could have been sold and fed into to the power grid. In this way, the surplus production would have contributed to the generation of income to the biorefinery instead of just representing a loss, as is the case with the surplus heat.

Table 4.8 On-site CHP: Input and output.

	Small-scale scenario		Large-scale scenario	
Input				
Biogas (55 % CH_4); m^3/tonne grass	5.34		16.10	
Total biogas (55 % CH_4); m^3	593,333		13,416,661	
Output	Heat (MJ)	Electricity (kWh)	Heat (MJ)	Electricity (kWh)
Total production; per tonne grass	52.8	10.26	159.44	31.01
Required for processing; per tonne grass	44.87	10.26	108.28	31.01
Surplus per tonne grass	7.93	-	51.16	-
Surplus (total)	881,110	-	42,633,316	-

In Section 4.1 the gross biogas production in each of the scenarios was assessed, and subtracting the amount of biogas required for producing energy for processing, the net biogas production available for up-grading can be estimated. For the small-scale scenario net biogas production is found to be 712,176 m^3, which is equivalent to approximately 6.4 m^3/tonne grass input and 35.6 m^3/tonne DM input. For the large-scale scenario net biogas production is found to be 34,694,038 m^3, which is equivalent to approximately 41.6 m^3/tonne grass input and 231.3 m^3/tonne DM input[7].

The net amount of biogas is fed into the upgrading unit, where biogas is converted into bio-methane with 96% CH_4, which corresponds to natural gas. The biomethane can subsequently be fed into the natural gas grid, where it substitutes fossil-based natural gas on a 1:1 basis. Upgrading reduces gas volume, while the heating value per cubic meter (LHV) is increased. During the upgrading process, part of the biogas is lost. Energistyrelsen (2016) estimates the loss to be 1.4 % in 2015, improving to 1.1 % in 2020, and 0.5 % in 2030. Correspondingly, the Biogas Industry has issued an Industry Declaration, where they specify that the goal is to reduce the methane slip from upgrading units to 1 % by 2020[8]. With reference to these loss estimates and targets, the methane slip at the upgrading unit is set to 1 %. Inputs and outputs of the upgrading unit are specified for the two scenarios in Table 4.9, which shows that total net biomethane production is 403,470 m^3 in the small-scale scenario, and 19,655,275 m^3 in the large-scale scenario. These figures reflect the amount of natural gas substituted in each scenario. The LHVs of biogas and biomethane used in the calculations are the same as in Njakou Djomo (2018).

[7] These estimates of net biogas production are slightly lower than the estimates listed in the flow diagrams in Annex 1. The difference is caused by inclusion of the 1% methane slip due to leakages.
[8] See: https://biogasbranchen.dk/viden/branchedeklarering.

Table 4.9 Upgrading unit: Inputs and outputs[1].

	Input (Biogas; 55 % CH_4, LHV=19,8 MJ/m^3): Biogas total (m^3)	Output (Biomethane; 96 % CH_4, LHV=34,6 MJ/m^3) Biomethane total (m^3)
Small-scale (Input to biogas: Juice DM=4,5 %)	712,176	403,470
Large-scale (Input to biogas: Juice & Fibre DM=16,4 %)	34,694,038	19,655,275

[1] Output has been adjusted to reflect 1 % methane slip during the upgrading process, just as the amount of input biogas has been adjusted to reflect the 1 % methane loss at the biogas plant. Due to these adjustments, the outputs listed here do not correspond exactly to the biomethane production estimates specified in the flow diagrams in Annex 1.

4.5 Investment, operation and maintenance

The investment requirement varies significantly between the two scenarios, as the large-scale scenario involves the construction of a new biogas plant while the small-scale scenario relies on capacity utilization at an existing plant.

4.5.1 Large-scale scenario – biogas plant

The annual biomass input to the biogas plant in the large-scale scenario is 760,833 tonnes, which is equivalent to 2,084 tonnes per day (see Table 4.2). Compared to existing biogas plants, this is a huge plant, comparable to some recently established, e.g. Maabjerg and Sønderjysk Biogas, which have annual processing capacities of 600-800,000 tonnes.

Biogas plant investment costs vary depending on the specific configuration of the plant (e.g. type of input, retention time, supply of energy for processing and scale) and the surrounding infrastructure / geographical location. Accordingly, actual investment costs will be case specific, and assessment of investment costs at a general level is bound to be associated with significant uncertainty.

Several studies dealing with economic analysis of biogas production in a Danish context provides estimates of biogas plant investment costs. One of these is Ea Energianalyse (2014), where the average total investment cost for a standard plant with an annual processing capacity in the interval 200-400,000 tonnes is estimated to 330 DKK / tonne input. Of these 275 DKK / tonne refer to investment in the biogas plant, while the remaining 55 DKK / tonne relate to investments in process heat facility, land purchase and "Miscellaneous". Miscellaneous is further broken down into advice, transport of gas and other. If the biomass input includes more "troublesome" types of biomasses, e.g. straw, grass clover or maize, investment costs are estimated to increase with 50 DKK / tonne. The case considered in Ea Energianalyse (2014) is different from our case in several respects; 1) scale of plant, 2) type of biomass, 3) production of energy for processing, and 4) transport of gas. The scale of the plant in our scenario is significantly larger than the scale of the plant in Ea Energianalyse (2014), and with reference to the theory of economics of scale, this suggests that the cost estimate from Ea Energianalyse (2014) should be revised downward, if to be used in our analysis. Similarly, it could be considered to subtract the investment costs related to transport of gas (approx. 5.5 DKK / tonne). On the other hand, the type of biomass used as input in our case (grass fibre with a high DM content) suggests that the basic cost from Ea Energianalyse (2104) should be adjusted upwards, e.g. by 50 DKK / tonne, which is the additional investment cost estimated for clover grass in Ea Energianalyse (2014). Likewise, the fact that we assume that the biogas plant is equipped with a biogas fired CHP rather than a straw fired kettle as assumed in Ea Energianlyse (2014) also suggests that the cost estimate should be revised upwards. In this context, it may be noted that the required capacity of the on-site CHP in our case probably is significantly higher than the normal capacity of units for producing process energy at biogas plant. Hence, the CHP not only needs to supply the energy demanded for processing at the biogas plant; it also needs to supply the energy required for processing at the protein part of the biorefinery and the electricity needed for upgrading. The on-site CHP unit needs to have a production capacity of approx. three MW in order to be able to cover the biorefinery's demand for electricity.

COWI (2013) presents economic analysis of a biogas plant with an annual processing capacity of 360,000 tonnes, and they estimate biogas plant investment costs to be 347-361 DKK/tonne depending on whether or not a land purchase (5 mDKK) is included or not. The cost estimate, among other items includes a gas kettle for producing energy as required for processing, but the specific contributions of the various cost elements to total costs are not further specified.

Hjort-Gregersen (2015) presents an analysis of biogas production based on data from 15 existing biogas plants, and the average investment cost for large-scale biogas plants is estimated to be 400 DKK/tonne processing capacity. This estimate is generic and has not been derived from a specific case, representing a crude average across large plants with different scales, configurations and input types.

The Maabjerg biogas plant is comparable to the plant considered in the large-scale scenario in terms of annual processing capacity. Hence, investment for the Maabjerg plant represents a relevant benchmark for the costs in our case. It follows from the Maabjerg homepage that investment costs (excl. transport and pipelines) for the plant was 319 mDKK, which with an annual biomass input of 800,000 tonnes corresponds to 399 DKK/tonne.[9]

The investment cost estimates from COWI (2013) and Ea Energianalyse (2014) suggests that investment costs for biogas plants approximately half the size of the plant considered in our large-scale scenario to be around 350 DKK/tonne for plants with a conventional input composition and around 400 DKK/tonne for plants treating more "troublesome" biomasses. With reference to economics of scale, it would be tempting to adjust this estimate downward, but with reference to the actual investment costs for the Maabjerg plant and the estimate of Hjort-Gregersen (2015), such adjustment would likely produce an underestimation. Hence, investment for the large-scale plant is set to 400 DKK/tonne; the resulting total investment for the large-scale scenario, along with the corresponding unit costs for the biorefinery are provided in Table 3.10. Total investment costs are annualized using the capital yield factor as described in Møller (2009). The capital yield factor depends on the lifetime of the investment and the discount rate. Here the physical and investment lifetime of the biogas plant is 20 years, and the discount rate is set to 7 %.

[9] https://www.maabjergenergycenter.dk/om-biogas/økonomi; https://www.maabjergenergycenter.dk/om-biogas

With reference to NIRAS (2012), the maintenance costs are assumed to be 4 % of annual investment costs, including required reinvestments.

Table 4.10 Biogas plant – investment costs and maintenance and reinvestment costs.

	Investment costs	Service and maintenance	Total
Total investment (mDKK)	304		304
Annual (DKK)	28,726,901	12,173,328	40,900,229
DKK/tonne grass input	34	15	49
DKK/tonne DM input	192	81	273
DKK/tonne gross biogas production	0.60	0.25	0.85
DKK/tonne biomass input	37.76	16.00	53.76
DKK/tonne biomethane for sale	1.46	62	2.08

4.5.2 Small-scale scenario – expansion of biogas production capacity at existing plant

In the small-scale scenario, where the amount of biomass for biogas is quite small and the biogas potential is modest, establishing a new plant based on liquid residue inputs from the small-scale protein plant is not considered an economically viable option. Rather, the biorefinery is connected to an existing biogas plant, where processing capacity is available to utilize the residue from the protein plant.

Ellegaard (2015) provides a formula for estimating the investment costs associated with expanding reactor capacity. The formula, which applies to reactors with a volume between 2-8.000 m^3, is:

Specific Volume Cost (DKK/m^3) = 1,285 DKK * (V/4,000)^-0.3

Ellegaard (2015) notes that his volume-based cost formula is likely to provide a lower bound estimate of actual cost. It does not include potential indirect costs related to e.g. additional heating capacity and biogas capacity, which are difficult to quantify on a general level. Specifically in relation to our scenario, it may be relevant to note that the estimate does not include expenses for additional storage facilities and expansion of CHP capacity. Hence, it is likely that it will be necessary with additional storage facilities. Whether or not it will be necessary to expand the capacity of the on-site CHP facility depends on the extent to which there is excess capacity at the existing CHP-facility. The energy required for processing at the small-scale biorefinery (incl. upgrading) corresponds to the energy produced by a 0.13 MW CHP unit. The modest demand for additional CHP capacity makes it reasonable to assume, that there is sufficient excess capacity at the existing CHP to produce the energy required for processing at the biorefinery.

According to Ea Energianalyse (2014) typical retention times for biogas production in Denmark are 16-18 days for thermophilic plants and 20-22 days for mesophilic plants. The retention time of the small-scale scenario is thus set to 20 days, and on this basis the required reactor capacity can be calculated to: (20 days * 60,111 tonnes)/365 days = 3,294 tonnes. Assuming that 1 tonne is equal to 1 m^3, and rounding, the required additional reactor capacity is approximately 3,500 m^3. Using the formula from Ellegaard (2015) the specific volume cost is 1,338 DKK/m^3, and total costs becomes 4,683,000 DKK. As pointed out above, this figure does not include all potential costs, some of which are difficult to quantify. It is therefore decided to top up costs by 20 % to reflect indirect costs associated with the capacity expansion, whereby total investment will be 5,619,600 DKK. Assuming a lifetime of 20 years and using an interest rate of 7 %, it corresponds to annual costs of 530,261 DKK. Based on Ellegaard (2015) service and maintenance is set to 0.5% of annual investment costs, corresponding to 28,088 DKK. Table 4.11 presents the costs to the small-scale scenario associated with expanding biogas production capacity, both in terms of total costs and in terms of the costs per unit of inputs and outputs.

Table 4.11 Expansion of biogas production capacity – costs.

	Investment costs	Service and maintenance	Total
Total investment (mDKK)	5.62		5.62
Annual (DKK)	530,261	28,088	558,349
DKK/tonne grass input	4.77	0.25	5.03
DKK/tonne DM input	26.51	1.40	27.92
DKK/tonne gross biogas production	0.89	0.05	0.94
DKK/tonne biomass input	8.82	0.47	9.29
DKK/tonne biomethane for sale	1.31	0.07	1.38

4.5.3 Upgrading and grid connection – large-scale scenario

Upgrading of biogas has been analyzed by Danish Energy Agency (2017), and an appended datasheet enables a calculation of upgrading costs per Nm^3 biomethane (see Table 4.12). The calculations are based on a technical lifetime of 15 years for the facility, and an interest rate of 7 %. The demand for electricity is omitted, as it does not represent a direct expense being included indirectly via the reduction in biogas available for upgrading. Upgrading costs are expected to decline over time (see Table 4.12).

Table 4.12 Biogas upgrading costs (DKK/Nm^3).

	2015	2020	2030	2050
Investment, upgrading	0.33	0.29	0.26	0.24
Investment grid injection	0.13	0.12	0.11	0.10
Operation and maintenance, upgrading	0.07	0.07	0.06	0.05
Operation and maintenance, grid injection	0.03	0.03	0.02	0.02
Total upgrading costs (DKK/Nm^3 biomethane)	0.56	0.51	0.46	0.41

The data used for estimating the upgrading costs presented in Table 4.12 refer to the pressure swing adsorption technology, and with a capacity of 594 Nm^3 biomethane per hour, which corresponds to approximately 5,000,000 Nm^3 per year. Alternative technologies would feature comparable costs for upgrading. The Danish Energy Agency (2017) data reflects the typical plant size, valid within a range of 500 – 1,500 Nm^3 biomethane per hour. For larger plants, the investment for upgrading is 20-25 % lower per volume unit added.

COWI (2013) presents data for biogas upgrading costs for a plant with an annual processing capacity of 9 million Nm^3 bio-methane, which is about twice the size of the typical plant considered in Danish Energy Agency (2017). According to COWI (2013) total upgrading and grid connection costs are 0.87 DKK/Nm^3 biomethane assuming a 20 year investment lifetime, while it increases to 1.1 DKK/Nm^3 biomethane if the lifetime is reduced to 10 years.

These costs are somewhat higher than the costs derived from Danish Energy Agency (2017), but not directly comparable as COWI (2013) differs on lifetime of the plant and includes electricity costs. When adjusting the lifetime to 15 years and omitting electricity costs, we find upgrading costs of 0.63 DKK / Nm^3 biomethane, of which 0.04 DKK relating to the pipeline. Costs for establishing a pipeline are not included in the estimates in Table 4.12, and it contribute partly to the difference between the COWI (2013) estimates and the estimates in Table 4.12.

The large-scale scenario involves the upgrading of approximately 20 million Nm^3 biomethane (equivalent to approximately 2,400 Nm^3/ hour), implying that the required processing capacity significantly exceeds the capacity of the model plants in COWI (2013) and Danish Energy Agency (2017). Danish Energy Agency (2017) suggests that there should be economies of scale, but limited (ibid., p. 35) once the input capacity exceeds 2,000 Nm^3 biogas. Hence, we abstain from adjusting our cost estimates. Upgrading costs for the large-scale scenario is assessed to 0.57 DKK / Nm^3 biomethane; representing the average cost for 2015 and 2020 (see Table 4.12) plus the 0.04 DKK / Nm^3 for establishing pipeline. With an annual biomethane production of 19,655,275 Nm^3 the total upgrading costs (excl. electricity) of the large-scale scenario becomes 11,203,507 DKK / year, corresponding to 13.4 DKK / tonne grass input and 74.7 DKK / tonne DM input.

The technical lifetime of the upgrading plant of 15 years is slightly at odds with the expected lifetime of the biogas plant of 20 years. Assuming that technical lifetimes should be interpreted as indicative, not providing an exact prediction of how long time a given plant can operate, we abstain from any corrections. Alternatively, the technical lifetime of the upgrading plant could be prolonged to 20 years (as done in COWI (2013)). Upgrading costs would thus be reduced, with the associated risk of underestimating true costs. Still, our approach does not hedge against any risk, as it might become necessary with additional investments in year 15.

4.5.4 Upgrading and grid connection – small-scale scenario

In the small-scale scenario, it is assumed that the biogas plant to be expanded has access to an operating upgrading facility. The biomethane production in the small-scale scenario is 400,000 Nm^3, which corresponds to approx. 50 Nm^3 per hour, whereby the additionally required capacity for upgrading is very small, considering the typical plant in Danish Energy Agency (2017) and the model plant in COWI (2013), with capacities of about 600 (594) and 1,100 (1,057) Nm^3/ hour respectively. The biomethane production of the small-scale scenario amounts to between 5 and 10 % of the model plants, and it is thus considered reasonable to assume that there is sufficient excess capacity at the existing facility to accommodate the additional amount of biogas for upgrading. This means that there are no investment costs and fixed operation and maintenance costs associated with the upgrading in the small-scale scenario. The only upgrading costs in the small-scale scenario are related to additional power consumption, which is not included as expenditures for the reasons explained above.

4.6 Input costs

In both scenarios, residues from the protein plant supply the entire biorefinery biomass input to biogas production, implying that the input is produced within the confines of the biorefinery. As the biorefinery is treated as an entity, the biogas plant does not have to pay for the input biomass, and the biogas plant hence has no direct expenses related to purchase of inputs.

In addition to biomass input, the biogas plant requires inputs of heat and electricity, just as the upgrading and grid connection facility requires input of electricity. As this energy required for processing is produced within the biorefinery, it does not represent actual expenses. Instead it enters the analysis as an indirect cost through the effect is has on net-biogas production.

4.7 Value of output

There are three outputs from the biogas plant; the digested biomass, the biogas used for processing at the biorefinery, and the bio-methane produced by upgrading net biogas production. The value of these three outputs will be discussed in the subsections below.

4.7.1 Value of digested biomass

The digested biomass is used as fertilizer for crops, substituting mineral fertilizer. As the grass for the biorefinery is assumed to be fertilised solely by the use of mineral fertilizer, the digestate is not relevant in that setting.

The nitrogen (N), phosphorous (P) and potassium (K) content of the digested biomass varies between the two scenarios due to differences in the residues used for biogas production. In the small-scale scenario, where only the liquid residue fraction is used for biogas, there is less nutrient content in the degassed biomass, compared to the large-scale scenario, where both fibre and liquid residue fractions are used for biogas production. The nutrient contents of the digested biomass, estimated based on the dry matter content of the grass input to the biorefinery, is presented in Table 4.13 along with the assumed utilisation rates. The utilisation rates are 40% for N respectively 100 % for P and K (Jensen, 2015; Gødningsbekendtgørelsen, 2018). The substitution rate of 40 % for N means that it is necessary to apply 2.5 kg N from degassed biomass in order to obtain the same first year effect as one gets from 1 kg of mineral fertilizer.

Table 4.13 Nutrient content of digested biomass and utilisation rates.

	Small-scale scenario	Large-scale scenario	Utilisation rate (%)
Nitrogen (kg N/tonne DM)	4.5	21	40
Phosphorous (kg P/tonne DM)	0.5	2.5	100
Potassium (kg K/tonne DM)	14.5	25	100

Based on the figures in Table 4.13, combined with the DM inputs of the two scenarios, the amounts of N, P and K in mineral fertilizers that can be substituted in each scenario is presented in Table 4.14. The economic fertilizer value of digested biomass is calculated based on the price of mineral N, P and K (6.3 DKK/kg N, 12 DKK/kg P and 5 DKK/kg K cf. Fog and Thierry, 2016). The economic fertilizer value of the digested biomass used for fertilizer is also listed in Table 4.14, revealing that the fertilizer value per tonne of input is more than twice as high when both fibre and juice is used for biogas production (large-scale scenario), in contrast to relying on juice only (small-scale scenario).

Table 4.14 Substituted mineral fertilizer and value of degassed biomass.

	Small-scale scenario	Large-scale scenario
Mineral N substituted (kg)	36,000	1,260,000
Mineral P substituted (kg)	10,000	375,000
Mineral K substituted (kg)	290,000	3,750,000
Value of N substitution (DKK)	226,800	7,938,0000
Value of P substitution (DKK)	120,000	4,500,000
Value of K substitution (DKK)	1,450,000	18,750,000
Fertilizer value of digested biomass		
Total (DKK)	1,796,800	31,188,000
DKK/tonne DM	90	208
DKK/tonne grass input	16	37
DKK/tonne degassed biomass	31	44

The fertilizer value listed in Table 4.14 does not represent the actual sales price of the degassed biomass, as it is necessary to adjust for the fertilizer application costs. The use of biomass as fertilizer does not make mineral fertilizers redundant as it will still be required to complement degassed biomass. As a result, the farmer will not save any costs related to the practical application of mineral fertilizer. Setting the application costs for the degassed biomass to 21 DKK/tonne, as done in Fog and Thierry (2016), the value per tonne degassed biomass is reduced. The implications of the adjustment for application costs to the economic fertilizervalue of degassed biomass used as fertilizer is presented in Table 4.15.

Table 4.15 Application cost adjusted fertilizer value of digested biomass.

	Small-scale scenario	Large-scale scenario
DKK/tonne degassed biomass	10	23
Total value (DKK)	569,476	16,383,000
DKK/tonne DM	28	109
DKK/tonne grass input	5	20

4.7.2 Value of biogas

The financial economic value of biogas – for use in CHP as well as for upgrading – is affected by taxes and subsidies. This section identifies the various taxes and subsidies relevant to biogas production and use, and estimates the sales value of the biogas that is upgraded. Subsequently the total value of biogas produced with the biorefinery scenarios will be presented.

Subsidies for biogas production and use

Production of renewable energy, including biogas production, is subsidized. For biogas, the subsidy is differentiated across different uses, e.g. process purposes, upgrading (biomethane), and heating. Two of these are relevant here, namely biogas for industrial process purposes and biogas for upgrading.

With regard to biogas used for industrial processes three different subsidies apply; a basic subsidy of 39 DKK/GJ, a price premium of 26 DKK/GJ and a temporary price premium of 10 DKK/GJ (cf. Amendments to the Law on Promotion of Renewable Energy passed on 4 July 2013[10]).

[10] See: https://www.retsinformation.dk/Forms/R0710.aspx?id=152758

While the basic subsidy is fixed, the price premium is subject to adjustment with reference to the market price of natural gas[11]. The temporary price premium has gradually been lowered with 2 DKK/GJ each year since 2016, whereby it will be phased out by the end of 2019. There are no explicit expiration dates for the other two elements, but according to EU State aid rules, the approval of the schemes by the European Commission, is limited to 10 years[12]. Whether the subsidies will continue in their current form after 2025[13] depends – among others – on whether or not EU approval will be granted for an additional period. However, other factors, such as the level of biogas support relative to support for other sources of renewable energy, are also likely to play an important role in how biogas will be subsidised in the future. The subsidy levels in 2017 for biogas to industrial processes is presented in Table 4.16.

The subsidies for biomethane are specified in the Law on Natural Gas supply[14], and the only difference compared to biogas used for process purposes relates to the basic subsidy. Thus, for biomethane, the basic subsidy is 79 DKK/GJ, and it is adjusted every year on 1 January according to 60 % of the increase in the net-price index in the previous year. The subsidization of biomethane also requires EU approval, and the current approval expires in 2023[15]. The subsidies applying to biomethane and the rates in 2017 are presented in Table 4.16.

Table 4.16 Biogas subsidies[1] (DKK_{2017}/GJ; see Appendix 1 for details regarding calculation of subsidy levels).

	Biogas used for process purposes	Upgraded biogas (biomethane)
Basic subsidy	39	81.3
26 DKK/GJ price premium	41.5	41.5
10 DKK/GJ price premium	6	6
Total	86.5	128.8

In order to calculate the value of the subsidies in the two scenarios it is necessary to assess the energy content of the biogas used for process purposes and the biogas used for upgrading. Referring to Section 4.5, 45 % of gross biogas production is used for processing in the small-scale scenario, and the corresponding share in the large-scale scenario is 28 %. Accordingly, the respective shares of gross biogas production destined for upgrading is 55 and 72 % in the two scenarios. Table 4.17 presents gross biogas production and the share used for processing and upgrading respectively.

11 The 26 DKK/GJ subsidy is adjusted on the 1 January every year based on the price of natural gas in the past year compared to a reference price of 53.2 DKK/GJ. If the natural gas price in the previous year was higher than the reference price, the price subsidy is decreased by the equivalent amount measured in DKK/GJ. If the natural gas price was lower than the reference price, the subsidy is increased by an equivalent amount measured in DKK/GJ. This calculation approach implies that the sum of the subsidy and the natural gas price cannot exceed 79.2 DKK/GJ, and accordingly the subsidy is reduced to zero if the natural gas price exceeds 79.2 DKK/GJ.
12 See e.g.: https://ens.dk/ansvarsomraader/bioenergi/stoette-til-biogas
13 The subsidisation of biogas used for process purposes was approved by the EU in 2015, and the subsidy scheme was implemented in 2016, see e.g.: http://www.mynewsdesk.com/dk/energistyrelsen/pressreleases/eu-har-godkendt-stoetten-til-biogas-1312041.
14 See: https://www.retsinformation.dk/Forms/r0710.aspx?id=183812
15 See e.g.: https://ens.dk/ansvarsomraader/bioenergi/stoette-til-biogas

Table 4.17 Gross biogas production, biogas used for processing and upgraded biogas.

	Gross biogas production		Biogas used for processing (CHP)		Biogas for upgrading	
	m³	GJ*	m³	GJ*	m³	GJ*
Small-scale scenario	1,305,509	25,849	593,333	11,748	712,176	14,101
Large-scale scenario	48,110,699	952,592	13,416,661	265,650	34,694,038	686,942

* Based on a LHV of 19.8 MJ/ m³.

Combining the figures of tables 4.16 and 4.17, the resulting total value of biogas subsidies in the two scenarios is shown in Table 4.18. The total value of subsidies is about 2.8 mDKK in the small-scale scenario, corresponding to 142 DKK per tonne DM grass input to the biorefinery. In the large-scale scenario, the total value of the subsidies is about 111 mDKK, which corresponds to 743 DKK per tonne DM input to the biorefinery.

Table 4.18 Value of subsidies.

	Small-scale scenario		Large-scale scenario	
	Biogas used for processing (CHP)	Biomethane	Biogas used for processing (CHP)	Biomethane
Basic subsidy	458,172	1,146,418	10,360,346	55,848,380
26 DKK/GJ price premium	487,542	585,195	11,024,471	25,508,091
10 DKK/GJ price premium (temporary)	70,488	84,606	1,593,899	4,121,652
Total	1,016,201	1,816,220	22,978,716	88,478,122
Total value of subsidies (DKK)		2,832,420		111,456,838
Value per tonne DM input (DKK/tonne DM		142		743
Value per tonne fresh grass (DKK/tonne)		25		134

Taxes on biogas use

The taxes imposed on biogas use are differentiated according to use. In relation to the biorefinery scenarios, it is relevant to distinguish between three different uses, namely 1) biogas used in the production of biogas, 2) biogas used for process purposes, and 3) biogas for upgrading.

The share of biogas used for producing the energy needed for operating the biogas plant falls within the category of "Biogas used in the production of biogas". The remaining share of biogas used at the on-site CHP, i.e. the share that is used to produce the energy required for operating the protein and upgrading plants, falls within the category of "Biogas used for process purposes". Finally, the amount of biogas in excess of what is needed for on-site energy production falls within the category "Biogas for upgrading". The amount of biogas in the latter category can be seen in Table 4.17. Table 4.19 shows the allocation of biogas used at the on-site CHP across the different process components (i.e. protein, biogas and upgrading plants) and use categories.

Table 4.19 Allocation of biogas used at on-site CHP across process components and use categories.

	Small-scale		Large-scale	
Process component	% of biogas	GJ	% of biogas	GJ
Protein plant	54	6,344	18	47,817
Biogas plant	31	3,642	50	132,825
Upgrading plant	15	1,762	32	85,008
Sum	100	11,748	100	265,650
Use category				
Biogas used in the production of biogas	31	3,642	50	132,825
Biogas used for process purposes	69	8,106	50	132,825
Sum	100	11,748	100	265,650

The taxes, which are relevant to consider in the context of biogas used for CHP production, fall into three categories according to their motivation[16]. One category is energy taxation, which aims at improving energy efficiency, and where the general principle is that all energy products should be taxed equally on basis of their energy content. A second category is Green House Gas (GHG) emissions taxation, which targets climate impacts from energy use. The GHG emissions taxes include a CO_2 tax, which applies only to energy use in sectors not covered by the EU Emissions Trading System (ETS), and a tax on methane emisisons. A third category is air pollution taxation, with taxes on NO_x emissions and SO_2 emissions. The rationale of air pollution taxes is that external costs associated with energy consumption should be reflected in the costs of fuels.

As taxes are imposed on the consumption (not the production) of fuels, there is no tax liability for the biomethane until it is used as input to energy production. Thus, the biorefinery does not have to pay any taxes related to the biomethane produced. We assume that the biomethane will replace natural gas for heat and power production elsewhere, so that taxes will be imposed on the biomethane at the consumption stage. Once the biomethane has entered the natural gas grid, it is taxed in the same way as natural gas[17]. It should also be noted that once the biomethane has entered the natural gas grid it cannot be distinguished from fossil-based natural gas, as there is no distinct grid infrastructure for biomethane. This means that it would be difficult to differentiate taxation between the two types of gases.

Biogas used in the production of biogas is exempt from all the taxes mentioned in the previous section[18], which implies that the biogas share, which supplies energy for running the biorefinery's biogas plant is not subject to taxation. With reference to Table 4.19 this implies that 31 % and 50 % of the biogas used at the on-site CHP in the small-scale scenario and large-scale scenario is exempt from taxation.

The tax exemptions do not apply to biogas used for process purposes. Thus, the share of biogas supplying the protein plant and the upgrading facility is subject to four different taxes: energy tax, methane tax, SO_2 tax and NO_x tax. It is not subject to CO_2 tax, as renewable energy is considered to be CO_2 neu-

[16] See e.g. Andersen (2016).
[17] See e.g.: https://ens.dk/ansvarsomraader/bioenergi/stoette-til-biogas
[18] See: https://skat.dk/skat.aspx?oid=2186129

tral, and is exempt from CO_2 taxation. The energy tax rate on biogas for processing is reduced compared to the standard energy tax on biogas use. The reduced energy tax rate is implemented with reimbursements, reducing the tax to 0.049 DKK/Nm^3 [19]. With a LHV of 39.6 MJ/Nm^3 the reduced tax rate for biogas used for processing at 0.049 DKK/Nm^3 is equivalent to a tax rate of 1.24 DKK/GJ. In addition to the energy tax, the biogas used for processing is subject to a methane tax of 1.2 DKK/GJ[20]. For the air pollution taxes, i.e. the tax on SO_2 and NO_x emissions, two different options exist; 1) a standard tax rate defined with reference to the sulphur content of the fuel (SO_2) or the energy content of the input fuel (NO_x tax), and 2) a rate referring to the actual emissions of SO_2 or NO_x. When opting for the standard rate there is no requirement for measuring emissions, which may be resource demanding. Still, we use the tax rates referring to actual emissions, assuming that the biorefinery is equipped with the necessary measurement instruments. The tax rate for SO_2 emissions is 11.7 DKK/kg, and the tax rate for NO_x emissions is 5.1 DKK/kg NO_2 equivalents emitted[21]. For comparison, the standard tax rates are 1 DKK/GJ for NO_x, and 23.3 DKK/kg sulphur in the fuel for SO_2. Table 4.20 shows total tax payments with the two scenarios, and comparing the figures of Table 4.18 and Table 4.20, it is evident tax liabilities are relatively minor compared to the economic value of subsidies.

Table 4.20 Taxes on biogas used for process purposes.

	Emissions coefficients[22]	Small-scale	Large-scale
Biogas used for process purposes (GJ)		8,106	132,825
Methane emissions (CH_4) (kg)	434 g/GJ	3,518	57,646
SO_2 emissions (kg)	19,2 g/GJ	156	2,550
NO_x emissions (kg)	202 g/GJ	1,637	26,831
	Tax rates		
Energy tax	1,24 DKK/GJ	10,052	164,703
Methane tax	1,2 DKK/GJ	9,727	159,390
SO_2 tax	11,7 DKK/kg	1,821	29,838
NO_x tax	5,1 DKK/kg	8,351	136,836
Total (DKK)		29,951	490,767

Sales price of biomethane

Both scenarios involve upgrading of biogas to biomethane. According to Table 4.17 the small-scale scenario involves upgrading of 14,101 GJ biogas, while 686,942 GJ biogas is upgraded in the large-scale scenario. This corresponds to approximately 55 % and 72 % of gross biogas production being upgraded in the small and large-scale scenario respectively. Adjusting for the 1 % biogas loss during the upgrading process (see Section 4.4) net biomethane production is 13,960 GJ in the small-scale scenario and 680,073 GJ in the large-scale scenario. As the biomethane is sold and fed into the natural gas grid, the sales price can be determined with reference to the price of natural gas; here a price of 38 DKK/GJ is used (Energistyrelsen 2017)[23]. The resulting total revenue

[19] See: http://skat.dk/skat.aspx?oId=2186134&chk=214955 .
[20] Methane tax applying to biogas used as fuel in stationary piston motor facilities with an input capacity of min. 1 MW; see: http://skat.dk/skat.aspx?oId=2186139&chk=214955
[21] See: https://www.pwc.dk/da/publikationer/2018/pwc-afgiftsvejledningen-2018.pdf
[22] For emissions coefficients see (Energistyrelsen 2017).
[23] See e.g. Appendix 1, where the natural gas price reported in Energistyrelsen (2017) is listed.

from sale of biomethane is shown in Table 4.21, along with the corresponding values per tonne of biorefinery input.

Table 4.21 Revenue from sale of biomethane.

	Small-scale	Large-scale
Biomethane for sale (GJ):	13,960	680,073
Total revenue (DKK):	530,483	25,842,756
Revenue per tonne DM input (DKK/tonne DM):	27	172
Revenue per tonne fresh grass (DKK/tonne):	5	31

Total value of biogas in the two scenarios

The total value of biogas produced under the two scenarios is determined by the sales price of biomethane, the taxes imposed on biogas use, and the subsidies granted for the different uses of biogas, as assessed above. The total value of the produced biogas is presented in Table 4.22.

Table 4.22 Total value of biogas.

	Total subsidy (DKK)	Total tax	Revenue from biomethane	Total value	Value per tonne DM input (DKK/tonne DM)	Value per tonne fresh grass (DKK/tonne)
Small-scale	2,832,420	29,951	530,483	3,332,952	167	30
Large-scale	111,456,838	490,767	25,842,756	136,808,827	912	164

It is clear from Table 4.22 that the value of biogas production when considered per tonne grass input and per tonne DM input varies significantly between the two scenarios. The main reason for these differences is that both fibre and juice residue fractions are used for biogas production in the large-scale scenario, while the juice fraction constitutes the only input to biogas production in the small-scale scenario.

Table 4.23 summarises for each of the two scenarios the various cost and revenue components identified in this chapter. Biomass input costs are not included, as these are accounted for in the analysis of the protein plant in Chapter 3.

Table 4.23 Overview of costs and revenues of biogas production.

	Small-scale plant		Large-scale plant	
Annual DM input (tonne):	20,000		150,000	
	Total (DKK/year)	Per tonne DM input (DKK/tonne DM)	Total (DKK/year)	Per tonne DM input (DKK/tonne DM)
Costs				
Labour	300,000	15	5,800,000	39
Energy	-	-	-	-
Investment – biogas plant	530,261	27	28,726,901	192
Maintenance – biogas plant	28,088	1	12,173,328	81
Investment - upgrading	-	-	11,558,974	77
Taxes	29,951	1	490,767	3
Total costs	*888,299*	*44*	*58,749,970*	*392*
Revenues				
Digested biomass	569,476	28	16,383,000	109
Sale of biomethane	530,483	27	25,842,756	172
Subsidies	2,832,420	142	111,456,838	743
Total revenues	*3,932,370*	*197*	*153,682,594*	*1,025*

5 Externalities and external costs

5.1 Greenhouse gases

The emission of greenhouse gases (GHG) contributes to climate change. The impacts of GHG emissions are to some extent internalized in the market through the imposition of GHG taxes and tradable allowances, but not all sources of GHG emissions are subject to regulation. Moreover, the tax levels and allowance prices do not necessarily correspond to the socio-economic costs of GHG emissions, while some GHG emissions are entirely unpriced. In the present section, GHG emissions related to the biorefinery scenarios are assessed and priced according to existing recommendations, with the aim of incorporating them into a socio-economic analysis.

Apart from CO_2, we focus on the GHG of N_2O (nitrogen dioxide) and CH_4 (methane). They are converted into CO_2 equivalents using the conversion factors of 298 (N_2O) and 25 (CH_4) (Energistyrelsen, 2017). This reflects that 1 tonne of N_2O has the same global warming potential (GWP) as 298 tonnes of CO_2, and that the GWP of 1 tonne of CH_4 is equivalent to that of 25 tonnes of CO_2.

There are several different sources of GHG emissions and the changes attributable to each of these when shifting from the baseline to the biorefinery scenarios will be considered in the following.

5.1.1 GHG emissions from CHP

In the small-scale scenario, 593,333 m^3 biogas is used at the on-site CHP, and the corresponding amount in the large-scale scenario is 13,416,661 m^3. Based on a LHV of 19.8 MJ / m^3, this is equivalent to 11,748 GJ and 265,650 GJ. Energy generation at the on-site CHP gives rise to emissions of CO_2, N_2O as well as CH_4, representing net increases in emissions. Emissions are calculated with standard coefficients for biogas fueled engines (Energistyrelsen, 2017), resulting in 133 tonnes and 3,009 tonnes for the small and large-scale scenario respectively (see Table 5.1). By far the largest share of these emissions is related to emissions of CH_4. The biogas emissions coefficient for CO_2 is 0; reflecting that biogas per definition is considered a CO_2 neutral fuel[24].

Table 5.1 GHG emissions from energy production at on-site biogas CHP.

	Emissions (g/GJ)		Small-scale (11,748 GJ) Total emissions (kg)	Total emissions (tonne CO_2 eq)	Large-scale (265,650 GJ) Total emissions (kg)	Total emissions (tonne CO_2 eq)
CO_2	0	1	-	-	-	-
N_2O	1.6	298	19	5.6	425	126.7
CH_4	434	25	5,099	127.5	115,292	2,882.3
Total CO_2 equivalents (tonne)				133		3,009

[24] The emissions coefficient for biogas used as engine fuel is 84.1 kg CO_2 / GJ (Nielsen et al., 2018a).

5.1.2 GHG emissions from leakages at biorefinery

As considered in Chapter 4, leakages at the biorefinery involves a methane slip, implying that some biogas is lost. Methane slippage at the biogas plant is estimated to 1 % of gross production, while the slippage at the upgrading unit is estimated to 1 % of the supplied biogas. Total GHG emissions from methane leakages at the biogas plant and the upgrading facility amount to 209 tonnes CO_2 eq. in the small-scale scenario and 8,589 tonnes in the large-scale scenario (see Table 5.2).

Table 5.2 GHG emissions from methane slips at biorefinery.

	Small-scale	Large-scale
Slippage, biogas plant (%)	1	1
Gross production (Nm^3)	1,318,696	48,596,666
Slip, biogas plant (Nm^3)	13,187	485,967
Slippage, upgrading facility (%)	1	1
Input to upgrading (Nm^3)	712,176	34,694,038
Slip, upgrading facility (Nm^3)	7,122	346,940
Total slip (Nm^3 biogas; 55 % CH_4)	20,309	832,907
Methane (tonne; density CH_4 = 0.75 kg/m^3)	8.4	343.6
CO_2 eq. (tonne)	209	8,589

[a] Slip estimate based on a methane density of 0.75 kg/m^3 (Jørgensen, 2009).

5.1.3 GHG reductions from substitution of natural gas with biomethane

Once biogas has been upgraded to biomethane and fed into the natural gas grid it is not possible to distinguish between biomethane and natural gas, and accordingly no distinction is made between the two. However, as biogas per definition is considered to be a CO_2 neutral fuel, biomethane could also be argued to be CO_2 neutral. Seen from this perspective, the substitution of conventional natural gas with biomethane translates into a reduction in CO_2 emissions. The biomethane production substituting natural gas is 13,960 GJ in the small-scale scenario and 680,073 GJ in the large-scale scenario (Table 4.21). The standard CO_2 emissions coefficient for natural gas is 57.1 kg / GJ (Energistyrelsen, 2017), and the resulting reductions can accordingly be calculated to 797 and 38,832 tonnes CO_2 for the small and large-scale scenarios, respectively.

5.1.4 Changes in GHG emissions related to land use and fertilizer substitution

The shift from cultivation of cereals to grass involves land use related changes in GHG emissions attributed to carbon sequestration, soil carbon content and N_2O emissions.

It follows from Knudsen and Mogensen (Annex 4) that the average carbon sequestration for grass is 800 kg CO_2 / ha / year, while it is –163 kg CO_2 / ha / year for cereals, whereby the transition to grass increases carbon sequestration with an average of 963 kg CO_2 / ha / year. For the small-scale scenario, where land use changes involve 2,010 ha, the total decrease in GHG emissions attributable to changes in carbon sequestration is 1,936 tonnes / year. For the large-scale scenario, where the affected agricultural area is 15,076 ha, the decrease in GHG emissions is 14,517 tonnes.

The substitution of mineral fertilizer with degassed biomass affects the carbon content of the soil, as part of the carbon content of the degassed biomass, which is applied to the fields will remain in the soil and contribute to building up soil carbon content. With C content of degassed biomass estimated to 0.45 kg C / kg DM, and assuming that 9.7 % of this C will be incorporated in the soil carbon pool (Marie Trydeman Knudsen, personal communication 2018), the increase becomes 0.04365 kg C / kg DM, which corresponds to a reduction in CO_2 emissions of 0.16 kg CO_2 / kg DM[25]. With a total DM content in the degassed biomass of 1,227 tonnes and of 70,500 tonnes, the annual GHG impact of the increased build-up of soil C can be calculated to -196.3 tonnes and -11,280 tonnes CO_2 equivalent for the small and large-scale scenarios, respectively.

The changes in N_2O emissions consist of direct changes related to emissions from crop residue and use of mineral fertilizer, and indirect changes associated with NH_3 and leaching. Based on Knudsen and Mogensen (Annex 4) the average direct N_2O emissions increase when shifting from cereals to intensive grass, while indirect N_2O emissions decrease. The increase in direct emissions is numerically greater than the decrease in indirect emissions, implying that the net result is an increase in N_2O emissions of 1,473 kg CO_2 eq / ha. The total increase in GHG from N_2O emissions related to land use change becomes 2,960 and 22,204 tonnes CO_2 eq for the small and large-scale scenarios, respectively.

Table 5.3 summarises the results on GHG emissions related to land use changes and the substitution of mineral fertilizer with degassed biomass. The net GHG impact differs between the two scenarios. For the large-scale scenario, the net effect is positive with a net reduction of GHG emissions, while for the small-scale scenario the opposite true. The main reason is related to the buildup of soil carbon due to the significantly higher DM content of the degassed biomass in the large-scale scenario.

Table 5.3 Changes in GHG emissions related to land use and changes in fertilizer use.

Source of change	Small-scale scenario (tonne CO_2 eq.)	Large-scale scenario (tonne CO_2 eq.)
Carbon sequestration (tonne/year)	- 1,936	- 14,517
Fertilizer substitution – change in Soil C (tonne/year)	- 196	- 11,280
N_2O emisisons – direct and indirect (tonne/year)	2,960	22,204
Net change (tonne/year)	828	- 3,593

5.1.5 Value of GHG emissions

Greenhouse gases of CO_2 are subject to pricing under the EU's emissions trading system. Emissions in sectors outside the EU ETS are valued in accordance with the European Commission's impact assessment for 2030 with a price of 40€$_{2010}$ / t CO_2. This is in line with recommendations from Denmark's Energy Agency. The ETS and Non-ETS CO_2 prices are presented in Table 5.4.

25 Conversion from kg C to kg CO_2 is based on the atomic weights of C (12) and O (16).

Table 5.4 ETS and Non-ETS CO_2 prices in 2017 prices.

Estimate of carbon price 2017-prices (DKK/tonne)	Estimate for ETS CO_2 price	Estimate for non-ETS CO_2 emissions
2020	156	156
2021	161	280
2022	167	290
2023	174	302
2024	181	313
2025	188	328
2026	197	343
2027	207	360
2028	217	378
2029	228	397
2030	240	418
2031	253	418
2032	267	418
2033	281	418
2034	296	418
2035	311	418
2036	327	418
2037	344	418
2038	363	418
2039	382	418

Considering the 20-year depreciation period for the biorefinery investment, we discount the average CO_2 price expectations in market prices (incl. the net charge factor) over a 20-year period, which results in an ETS price of DKK 216 and a non-ETS price of DKK 329 per tonne CO_2.

Table 5.5 summarizes the net changes in GHG emissions associated with the two scenarios. It should be noted that any GHG changes outside Denmark are not included, and this should be borne in mind when interpreting the results. Changes in GHG emissions related to land use changes in soy producing countries and to production of mineral fertilizers for intensive grass production are omitted according to the methodology prescribed by the Ministry of Finance. However, we return to the significance of this approach in the final discussion chapter.

The overall result is a net increase in GHG emissions in the small-scale scenario, while there is a significant net decrease in the large-scale scenario. This difference is caused by the greater amount of biomethane produced, also per unit of biomass input, in the large-scale scenario compared to the small-scale scenario. The total value of the change in GHG emissions is estimated to represent a net cost of approximately 213,000 DKK in the small-scale scenario, and a net benefit of approximately 5.8 mDKK in the large-scale scenario.

Table 5.5 Total change in GHG (tonne CO_2 equivalents; excl. transport).

	Small-scale		Large-scale	
	ETS	Non-ETS	ETS	Non-ETS
Energy production at on-site CHP		133		3,009
Methane slippage at biorefiney		209		8,589
Land use and fertilizer use		828		- 3593
Substitution of natural gas with biomethane	- 797		- 38,832	
Total change in GHG	- 797	1,170	- 38,832	8,005
CO_2 eq price	216	329	216	329
Value of change (DKK)	172,178	- 385,073	8,387,742	- 2,633,761
Total value (ETS and non-ETS; DKK)	- 212,895		5,753,981	

5.2 Air pollution

Air pollution is caused by the on-site CHP plant, as well as by changes in the demand for transport and use of agricultural machinery. The latter are covered in the section on transport externalities further below.

Air pollutants originating from the heat and electricity production at the on-site CHP can be estimated based on biogas energy content (cf. Table 4.17) and with standard emission coefficients for biogas based CHP production (cf. Nielsen et al., 2018a).

The average cost of air pollution per GJ is 2.5 DKK in both scenarios. It should be noted that only the emissions for which a price has been identified are included[26]. The external cost estimates for SO_2, NO_x and $PM_{2.5}$ are valid for emissions from the energy-producing sector (SNAP1). External costs of air pollution originating from energy production in Denmark, but arising in other countries are omitted, as prescribed by the Ministry of Finance. The costs, adjusted to 2017-prices, are preference based (Andersen, Brandt and Frohn Rasmussen 2019).

Table 5.6 External cost of air pollution from energy production at biorefinery.

			Small-scale		Large-scale	
	Emission coefficient	External cost (DKK/kg)	Emissions (kg)	External cost (DKK)	Emissions (kg)	External cost (DKK)
SO_2	19.2 g/GJ	12.06	225.6	2,720	5,100.48	61,512
NO_x	202 g/GJ	10.96	2,373.1	26,009	53,661.30	588,128
$PM_{2.5}$	0.206 g/GJ	55.65	2.4	135	54.72	3,045
Total external costs (DKK)				28,865		652,685
Average external costs (DKK/GJ)				2.5		2.5

5.3 Nitrogen

The shift from the baseline scenario to the biorefinery scenarios cause changes in nitrogen (N) leaching. These changes can be attributed to two factors: 1) changes in arable crops and the associated fertilizer use (grass vs. cereals), and 2) substitution of mineral fertilizer with degassed biomass (i.e. the residual product from biogas production). The leaching of N to the root zone of croplands, and subsequently to various water bodies (streams, groundwater,

[26] Lead emissions from CHP production are 59 and 1,328 mg in the two scenarios, respectively, implying that external costs are minimal, despite a unit cost of 3,260 DKK/kg (Andersen and Brandt, 2014).

lakes and coastal and marine waters) influences water quality with implications for human welfare that can be monetized.

The changes in N-leaching implicated by changes in the level of fertilizer use is presented in Table 5.7. They are based on the assumption that both cereals and grass are fertilized entirely with mineral fertilizers (i.e. no use of manure). The figures refer to leaching from the root-zone and they are based on Knudsen and Mogensen (Annex 4). N leaching is reduced in both scenarios, although the amount of fertilizer applied is significantly higher in the biorefinery scenarios than in the baseline scenarios with cereal production.

When mineral fertilizer is substituted with degassed biomass, the total amount of N applied per hectare needs to be increased as in the short run only the share of inorganic N in the degassed biomass is available to the plants. Based on the prescribed utilisation rate for N in degassed biomass of 40 % (Jensen, 2015; BEK nr 1008 af 02 / 07 / 2018), there is an unused fraction of 60 %, increasing long-run N leaching. In the small-scale scenario, the total amount of N in the degassed biomass is 90 tonnes (4.5 kg N per tonne DM grass input to the biorefinery), and the amount of mineral N being substituted is 36 tonnes (Table 4.14), implying that the surplus in this scenario is 54 tonnes. The corresponding amounts for the large-scale scenario are 3,150 tonnes (21 kg N per tonne DM grass input to biorefinery), 1,260 tonnes (substituted mineral fertilizer), and 1,890 tonnes (surplus). Part of the surplus is incorporated into the soil together with carbon, and there are other retention processes, whereby actual increase in leaching is less than the surplus. Based on the conventional formula used to assess the mineralization process of organic N (Petersen and Sørensen, 2008) we should expect a long-run leaching rate of 36 %.

In Table 5.7, it is seen that there is a net increase in N leaching in both scenarios, while the magnitude of the increase varies across the scenarios. The reason for this difference is the higher N content of the degassed biomass in the large-scale scenario, due to the use of both juice and fibre as input to biogas production.

Table 5.7 Changes in N leaching to the rootzone due to changes in fertilizer application and substitution of fertilizers.

	Small-scale scenario	Large-scale scenario
Changes in N leaching due to changes in fertilizer application		
Average change in N application (kgN/ha/year)	287	287
Total change in N application (tonne)	577	4,327
Average N leaching cereal production (kgN/ha/year)	62.41	62.41
Average N leaching grass production (kgN/ha/year)	47.16	47.16
Average change in N leaching (kgN/ha/year)	-15.25	-15.25
Total change in short-run N leaching (tonne N/year)	-30.65	-229.88
Changes in N leaching due to substitution of synthetic fertilizer with degassed biomass		
Total N in degassed biomass (tonne)	90	3,150
N utilised by plants (tonne)	36	1,260
Long-run N leaching to rootzone (tonne)	32.4	1,134
Total change in N leaching (tonne)	1.8	904

N-leaching has a negative effect on coastal and marine water bodies, where it leads to eutrophication and loss of water clarity. The monetary benefits of changes in N leaching to coastal water bodies have been estimated for Denmark, based on studies of implications for real estate owners, beachgoers and other residents (Andersen, Levin and Odgaard, 2018). The valuation result for eight polyhaline estuaries of DKK 14.9 / kgN provides only partial coverage of impacts, so it is considered more appropriate to use the current shadow cost price for nitrogen abatement measures of DKK 25 / kgN (Jacobsen, 2017). In comparison the shadow price is slightly lower than the nitrogen tax rate of DKK 30 / kgN for point sources in legislation. The external costs inflicted by N leaching from degassed biomass will emerge only in the long run, and for this purpose the shadow price is discounted (20 years; DKK 11 / kgN).

The results are presented in Table 5.8, showing that net outcomes in the small and large-scale scenarios respectively amount to external benefits of 409,850 and costs of 6,727,000 DKK.

Table 5.8 Value of changes in N leaching.

	Shadow price ($DKK_{2017}/kgN_{rootzone}$)	Small-scale scenario (DKK)	Large-scale scenario (DKK)
N leaching change from shifting to grass	25	-766,250	-5,747,000
N leaching from degassed biomass	11	356,400	12,474,000
Net external costs related to nitrogen		-409,850	6,727,000

NB: Negative costs denote environmental benefits.

5.4 Phosphorous

The shift from the baseline of cereal production to the biorefinery scenarios with intensive grass crops has consequences for the leaching of phosphorous (P). The estimated changes for each of the two scenarios are presented in Table 5.9. While P-application increases, the leaching of P is reduced.

P-leaching has implications for water bodies of freshwater, and reductions represents a positive value to society.

Emissions of phosphorous are taxed according to the law on wastewater taxes at 165 DKK per kg total P[27]. We use this tax rate as a reference, and when adjusting it with the net tax factor of 1.28, the value of reduced P leaching in the two scenarios can be assessed to 68,851 DKK in the small-scale scenario and 517,229 DKK in the large-scale scenario. In the absence of damage cost estimates of P leaching, the tax rate reflects the politically determined costs of emitting P to surface waters.

Table 5.9 Changes in P leaching due to changes in the level of fertilizer application[1].

	Average change in P application (kg P/ha/year)	Average P leaching cereal production (kg P/ha/year)	Average P leaching grass production (kg P/ha/year)	Average change in P leaching (kg P/ha/year)	Total change in P leaching (kg P/year)
Small-scale scenario	13	-0.04	-0.20	-0.16	-326
Large-scale scenario	13	-0.04	-0.20	-0.16	-2.449

[1] The changes in P leaching has been assed based on "Crop production spread sheet".

[27] See https: / / www.skm.dk / skattetal / satser / satser-og-be-loebsgraenser / spildevandsafgiftsloven

5.5 Ammonia (NH_3) emissions due to land use change

Fertilizer use gives rise to ammonia emissions, and when crop residues are left in the field, ammonia is also emitted during decomposition. The level of ammonia emissions from cultivation of cereals and grass differ. Based on Knudsen and Mogensen (Annex 4) the changes in ammonia emissions between the baseline and the biorefinery scenarios are as shown in Table 5.10.

The two sources of ammonia emissions change in different directions when shifting from the baseline scenario to the biorefinery scenarios; emissions attributable to the use of fertilizer increase, while emissions from crop residues decrease. The net effect, however, is a significant increase in total ammonia emissions.

Table 5.10 Changes in ammonia emissions due to fertilizer use and crop residues.

	Change due to changed use of fertilizer		Change due to crop residue changes		Net change in NH_3 emissions (tonne)
	kg/ha	Total (tonne)	kg/ha	Total (tonne)	
Small-scale	6,3	12,68	-1,5	-3,0	9,7
Large-scale	6,3	95,1	-1,5	-22,6	72,5

Ammonia interacts in the atmosphere with other air pollutants and extend their lifetime, increasing the mass of secondary particles ($PM_{2.5}$), having negative health impacts in terms of morbidity and early mortality. The costs of ammonia emissions have been assessed with the EVA model by Andersen, Frohn Rasmussen and Brandt (2019), who find external cost of NH_3 emissions from agriculture (SNAP10) of 150 DKK/kg. Their atmospheric modelling shows that 17 % of the impacts are incurred in Denmark, remaining within a national scope of analysis, the domestic external costs are 25.5 DKK/kg. For the two scenarios, it results in external costs of DKK 247,350 and DKK 1,848,750.

However, following OECD (2018) costs and benefits inflicted abroad should be included in cost-benefit analysis when preferences of other countries have been recognized under a legally binding international agreement. With regard to NH_3 Denmark is commited to reduce emissions by 24 % by 2020 compared to the reference year of 2005[28]. The most recent projections of Danish NH_3 emissions indicate that they will be reduced by approximately 18 % in 2020 and by approximately 19 % in 2030 (Nielsen et al. 2018b), whereby Denmark will fall short of its target.

Using an external cost estimate for non-domestic NH_3 emissions of 124.5 DKK/kg[29], the additional external costs associated with increasing NH_3 emissions due to changes in fertilizer use and changes related to the amount of crop residue left in the field would be assessed to 1.2 mDKK in the small-scale scenario and 9 mDKK in the large-scale scenario. This illustrates how the national delimination can influence results. Any increases in NH_3 emissions represent a challenge to the two scenarios as long as the additional measures for accomplishing Denmark's reduction target have not been reported to the EU.

[28] See e.g. https://eur-lex.europa.eu/legal-content/DA/TXT/PDF/?uri=CELEX:32016L2284&from=EN .

[29] The external cost of 124.5 DKK/kg is calculated by multiplying the external cost of 150 DKK/kg by the share of non-domestic damage costs (i.e. 83 %).

5.6 Heavy metals

The two primary sources of heavy metals are deposition and mineral fertilizers, but a small contribution also comes from seeds. Deposition is not related to land use, while the amount of heavy metals originating from mineral fertilizers depends on the amount and type of fertilizers used (see Table A3.1 in Appendix 3); The heavy metals considered include Cadmium, (Cd), Chromium (Cr), Copper (Cu), Lead (Pb), Mercury (Hg), Nickel (Ni) and Zinc (Zn).

A share of heavy metals are removed with crops, while other shares remain in the soil or leach to water bodies (see Table A3.1 in Appendix 3). The direction and magnitude of the changes vary among the different heavy metals considered. Taking Zn as an example there is an increase in leaching, but a decrease in emissions to soil; the net effect is a decrease. Generally, the impacts in terms of emissions to soil is greater than on leaching.

Heavy metals emitted to the soil and leaching to water represent external impacts, due to their potential negative effects on the environment and human health. However, these effects vary considerably, and unfortunately, reliable valuation estimates are not available for most substances. Still, a recent study by Pizzol et al. (2014) estimate the external costs of cadmium emission to soil arising from impacts related to osteoporosis among women through food with cadmium traces from phosphorus fertilizers. The estimate is preference based, and is relevant for assessing the external costs of cadmium in the present study. Their results have been adjusted to be consistent with the valuation of a healthy life year presently applied[30], whereby the external cost is 10.43 DKK per g cadmium applied. With reference to Table A3.1 in Appendix 3, the average increase in the amount of cadmium applied when shifting from cereals to grass is 2,913 mg / ha[31] . Accordingly, the total cadmium input in the small-scale scenario (2,010 ha) is 5,855.1 g and in the large-scale scenario (15,076 ha) 43,916 g. Thus, the external costs of cadmium amount to 61,069 DKK and 458,048 DKK in the small and large-scale scenarios, respectively.

5.7 Pesticides

Chemical plant protection, i.e. pesticides, fungicides, insecticides and herbicides, is jointly referred to as pesticides. There are concerns about the negative impacts that pesticides may have on biodiversity and human health, e.g. due to the decomposition of pesticides in groundwater used for drinking water purposes.

The extent to which the shift from cereal production to intensive grass production is associated with positive or negative changes in the use of pesticides can be gauged based on Knudsen and Mogensen (Annex 4). The changes in emissions to air, water and soil of herbicides, pesticides, fungicides, insecticides and glyphosate associated with shifting from the baseline scenarios to the biorefinery scenarios are presented in Table 5.11. It should be noted that the calculations are based on the assumption that 17 % of the active ingredients are lost to air, while 1 % and 45 % are lost to water and soil, respectively.

[30] Pizzol et al. (2014) base their cost estimate on a Value of Life Year (VOLY) of 40,000 EUR; the cost estimate used in this study has been adjusted to reflect a VOLY of 149,594, which is consistent with the value used in the EVA (Economic Valuation of Air Pollution) modelling system used to assess the external costs of air pollution.
[31] This estimate includes cadmium input in connection with both seeds and fertilizers, but the amount applied together with the seeds only constitute a negligible share.

In total, this implies that 63 % of the active ingredients are lost. The figures in Table 5.11 refer to the amount of active ingredients, not to the toxicity of the compounds.

The change in land use has no impact on the use of glyphosate, while for the other four pesticide categories it causes a decrease in the amount of active ingredients emitted to air, water and soil (see Table 5.11). The results suggest that the shift from the baseline scenario to the biorefinery scenarios leads to a reduction in the risks to biodiversity and human health associated with pesticide use. However, as the assessment is based on the amount of active ingredients rather than the toxicity of the individual pesticides, it is not possible to draw any definite conclusions as to the actual implications of changes in pesticide use. Moreover, due to lack of knowledge about dose-response relationships and the valuation of potential impacts on biodiversity and human health it would not be not possible to derive a monetary value. Nevertheless, it seems safe to observe that the land use changes do not aggravate the potential problems associated with pesticide use.

In Denmark, a tax is imposed on pesticides. The pesticide taxation scheme was changed in 2013 from a value-based tax to a differentiated tax, based on the environmental and health properties of the agents. The new tax scheme has a basic tax of 50 DKK per kg active ingredient plus a differentiated tax of 107 DKK per pesticide load unit (Miljøstyrelsen, 2018). Thus, the price of pesticides, which are included in the analyses as part of the cultivation costs, to some extent reflect the external health and environmental costs of pesticide use.

The pesticide load is assessed with reference to the generic health and environmental properties of the individual ingredients, but without an actual exposure assessment. Thus, it should be noted that all pesticides used in Denmark have to be approved, contingent upon a positive evaluation of the risks associated with the products. Products can only be approved if they are not expected to cause undesirable impacts on human health and the environment (Miljøstyrelsen, 2012).

Table 5.11 Changes in emissions from different pesticides (changes assessed in kg active ingredient (a.i.).

	Herbicides		Pesticides		Fungicides		Insecticides		Glyphosate	
	Change (kg a.i./ha)	Relative change (%)	Change (kg a.i./ha)	Relative change (%)	Change (kg a.i./ha)	Relative change (%)	Change (kg a.i./ha)	Relative change (%)	Change (kg a.i./ha)	Relative change (%)
To air	-0.1196	-96	-0.0273	-100	-0.0350	95	-0.0026	-66	0	0
To water	-0.0070	-96	-0.0016	-100	-0.0021	95	-0.0002	-66	0	0
To soil	-0.3166	-96	-0.0722	-100	-0.927	95	-0.0070	-66	0	0

Small-scale (total changes, kg a.i)	Herbicides	Pesticides	Fungicides	Insecticides	Glyphosate
To air	- 240.39	- 54.84	- 70.39	- 5.30	-
To water	- 14.14	- 3.23	- 4.14	- 0.31	-
To soil	- 636.32	- 145.17	- 186.33	- 14.02	-

Large-scale (total changes, kg a.i.)	Herbicides	Pesticides	Fungicides	Insecticides	Glyphosate
To air	- 1,803.01	- 411.35	- 527.96	- 39.73	-
To water	- 106.06	- 24.20	- 31.06	- 2.34	-
To soil	- 4,772.68	- 1,088.86	- 1.397.55	- 105.16	-

5.8 Transport

With the change from cereals to intensive grass crops, less fieldwork will be required as plowing, harrowing and sowing will be necessary only every four years rather than every year. On the other hand, grass crops are more voluminous and require more capacity for road transport.

The reduction in diesel use for fieldwork is calculated based on Knudsen and Mogensen (Annex 4), and the results are shown in Table 5.12. The shift from cereals to intensive grass crops causes a 10 % reduction in the amount of diesel required for field work. The direct costs of diesel are included with the cultivation, harvesting and transportation costs reviewed in Chapter 3, so focus here is on the external costs associated with agricultural machinery diesel use.

Table 5.12 Change in diesel required for field operations.

	Baseline	Small-scale – scenario change			Large-scale – scenario change		
	liter/ha	liter/ha	%	liter total	liter/ha	%	liter total
Diesel for field work	87	-9	-10	-18,090	-9	-10	-135,684

Table 5.13 shows the increased volume of outputs that needs to be transported away from the field when shifting from cereals to grass, which is about eight times greater with grass compared to cereals.

Table 5.13 Yields and yield changes with grass production.

Lorry transport of yield	Yield - kg/ha
Barley	5,592
Wheat	6,875
Average Barley/Wheat	6,234
Grass	55,277
Difference	49,044
Difference (%)	787

Based on the increased weight of agricultural output (see Table 5.13), the increased demand for lorry transport of agricultural yields is shown in Table 5.14. The calculations are based on an average lorry capacity of 23 tonnes, and return trip distances of 10 and 20 km for the small and large-scale scenarios, respectively.

Table 5.14 Change in mileage (in km) required for lorry transports of yield. Average lorry capacity.

Increased yield	Lorry capacity	Small-scale scenario change			Large-scale scenario change		
tonne/ha	tonne	tonne extra	Trips extra	km extra (return)	tonne extra	Trips extra	km extra (return)
49.044	23	98,577	4,286	42,860	739,380	32,147	642,939

The external costs of transport feature several different elements including air pollution, greenhouse gas (GHG) emissions, noise, accidents, infrastructure wear and congestion. In this project non-road as well as road transport vehicles are involved. Non-road vehicles are required for the field operations, whereas road transport vehicles take the grass harvest to the biorefinery.

Non-road transport

The GHG and air pollution emissions from the diesel use associated with field operations and the monetary valuation is shown in Table 5.15. The transport economic prices TERESA (TRM, 2018) do not feature agricultural machinery, so prices have been calculated based on the emission factors specified in Annex 3B-15-2 of DCE report 272 for agricultural vehicles (Nielsen et al., 2018a), and the environmental economic unit prices relating to Denmark for SNAP 8, referring to non-road driving patterns (Andersen, Frohn Rasmussen and Brandt, 2019). The unit costs of GHG are the same as in the section above for non-ETS emissions. The external costs of GHG and air pollutants sum to DKK 1.86 per liter diesel.

Table 5.15 External costs of greenhouse gases and air pollutants from motor fuel diesel used for off-road agricultural machinery operations (SNAP8) with 0.035109 GJ per liter diesel. NB: 2017 prices[32].

	SO_2	NO_x	$PM_{2.5}$	CO_2	N_2O	CH_4	Total
g/GJ	0.47	403.40	27.82	74,000	3.51	0.96	
g/liter	0.016	14.163	0.977	2598.066	0.123	0.034	
DKK/kg	62.30	53.48	439.04	0.257	76.48	6.42	
DKK/liter	0.001	0.76	0.43	0.67	0.009	0.000	1.86

For field operations, the costs of congestion and infrastructure are not considered relevant, whereas costs of noise and accidents needs to be estimated. In the absence of specific estimates for non-road machinery, we refer to the average value for lorries in rural areas of DKK 1.90 per kilometer (TRM, 2018). With an estimated fuel use of 5 liter per hectare and a mower width of 12 meter, we come to a fuel efficiency of 0.17 km per liter, whereby the costs of noise and accidents per liter diesel amounts to DKK 0.32. Thus, the total external costs per liter diesel sum to DKK 2.18.

With a reduction in diesel consumption for field work of 18,090 liter and 135,684 liter the reduction in external costs can be calculated to 39,436 DKK in the small-scale scenario and 295,791 DKK in the large-scale scenario.

Road transport

The transport economic unit prices TERESA specify the external costs per kilometer, while accounting for air pollution, GHG, noise, accidents, congestion and infrastructure wear. We use the values for an average lorry of 23 tonnes. For consistency, we updated and recalculated the costs of air pollutants with the more recent emissions factors of 2016. The external costs, as shown in Table 5.16, sum to DKK 4.84 per km.

Table 5.16 External costs per km of road transport of grass harvest with lorries to biorefinery (DKK/km).

	Air pollution	Climate	Noise	Accidents	Congestion	Infrastruct.	Total
DKK/km	0.65	0.15	0.05	1.78	0.64	1.56	4.84

The road transport distances for the large and small plants amount to 10 and 20 km, respectively, for a lorry return trip, whereby the external costs are DKK 48, respectively DKK 96, per return trip. In the small-scale scenario, where the number of extra trips is 4,286, the total external costs related to additional

[32] Same CO_2 price as above for non-ETS.

lorry transport becomes 207,441 DKK, while in the large-scale scenario with 32,147 extra trips total external costs sum to 3,111,825 DKK.

Table 5.17 Environmentally related externalities of the two scenarios.

Externalities	Small-scale scenario		Large-scale scenario	
	Total (DKK/year)	DKK/tonne DM input	Total (DKK/year)	DKK/tonne DM input
GHG emissions	-212,895	-11	5,753,981	38
Air pollution	-28,865	-1	-652,685	- 4
N leaching	409,850	20	- 6,727,000	- 45
P leaching	68,851	3	517,229	3
Ammonia emissions	-247,350	-12	- 1,848,750	- 12
Cadmium	-61,069	-3	- 458,048	- 3
Non road transport (field work)	39,436	2	295,791	2
Road transport	-207,441	-10	- 3,111,825	- 21
Net value of external impacts	-239,483	-12	- 6,231,306	-42
Ammonia damages, additional external costs with non-attainment of reduction target for Denmark	-1,207,650	-60	-9,026,250	-60
Gross value of external impacts incl. non-domestic ammonia damages	-1,447,133	-72	-15,257,556	- 102

6 Financial economic analysis and results

Financial analysis refers to assessment of the monetary costs and revenues of a project, and by considering the monetary flows between different stakeholders, it can be used to identify which stakeholders are likely to benefit and which are likely to incur a monetary loss. Financial analysis addresses goods and services traded on the market, and external costs are not included.

Financial analysis is based on factor prices, which reflect the price of production factors. Factor prices represent the prices that producers receive for their goods, and they are equal to market prices minus taxes and subsidies.

Assessment of the financial economic profitability can either be based on the net present value of the project, which represents the sum of the projects net benefits discounted over the lifetime of the investment / project, or – if net-benefits are assumed to be constant over the investment lifetime – on the net-benefits of a single year. When there are initial investment costs associated with a project, it is necessary to annualize these, to distribute investment costs evenly across the entire project lifetime. The discount rate used for discounting net-benefits or annualizing investment costs should reflect the required return on investments, i.e. the expected rate of return of alternative investments. If the financial economic analysis returns a positive net result it means that the analyzed project – based on the given assumptions – can be expected to yield a higher return than that of the discount rate. From a private investor's point of view, this suggests that the analyzed project represents a worthwhile investment, as it yields a higher return than alternative investments. The commercial discount rate is fixed to 7 % in the present analysis (see chapters 3 and 4). Considering the modest level of current interest rates, it could be argued that 7 % is a rather high, and perhaps unrealistic, required return of investment. On the other hand, recent large-scale biogas projects have offered participating farmers the prospect of a 10 % rate of return. This indicates that 7 % represents a reasonable discount rate. The significance of the interest rate to the overall profitability of biorefineries is further explored in the sensitivity analysis presented in Chapter 8.

The assessment of the financial economic profitability of the scenarios in the present report is based on the assumption that net-benefits are constant over the lifetime of the biorefineries, despite expectations that several – if not all – of the underlying prices are likely to change over the lifetime of the project. Making predictions about how prices will change over the next 15 to 20 years is bound to be associated with significant uncertainty, and would easily introduce as much uncertainty as the assumption of constant net-benefits. By choosing the constant net-benefit approach, rather than attempt predictions about future price changes, we believe the analysis will be more transparent, allowing for subsequent sensitivity analysis.

Based on the results in chapters 3 and 4, the financial economic profitability of the biorefinery scenarios are presented in Table 6.1. The figures reflect the annual consequences associated with shifting from the baseline scenario, to the scenarios with biorefineries producing green protein and biogas.

There are two relevant stakeholders: the biorefinery and the treasury. Even though the treasury is not an active stakeholder in the biorefinery set-up as such, it nevertheless becomes involved as biogas generation and consumption is subject to subsidies as well as certain taxes, with implications for government finances. Although farmers are expected to play a key role as suppliers of biomass, they do not represent a stakeholder as such in the financial economic analysis. Farmers are assumed to be compensated for the potential losses incurred by the changes in land use, just as they are assumed to pay for potential benefits (e.g. fertilizer value of digested biomass). Hence, seen from a strictly financial economic perspective farmers are assumed not to be affected by the shift from the baseline scenarios to the biorefinery scenarios, and thereby they are expected to be indifferent between the two.

Both scenarios represent a significant net expense to the State (see Table 6.1), caused by the obligation to provide subsidies for biogas production, which significantly exceed the revenues from taxes imposed on biogas used for process purposes. The net expense for the state per tonne DM input varies significantly between the two scenarios with a financial loss per tonne DM in the large-scale scenario of more than five times the loss in the small-scale scenario. This difference is due to the much lower biogas production per tonne input in the small-scale scenario compared to the large-scale scenario.

Based on the results presented in Table 6.1 it is not possible to say anything definite about the financial economic profitability to biorefinery owners. While the net result for biorefinery owners is positive in the small-scale scenario, the net result is negative for the large-scale scenario, suggesting that profitability depends on the specific configuration of biorefinery production processes. Both costs and revenues per tonne DM input are higher in the large-scale scenario than in the small-scale scenario, however the relative increase in costs is larger than the relative increase in revenue, whereby the net effect is a deficit for the large-scale biorefinery owners. Still, it should be noted that the net profit / deficit per tonne of input is relatively small in both scenarios, suggesting that even fairly minor changes in estimated costs or revenues could change the sign of the net results. Thus, for the small-scale scenario a decrease in revenue of less than 5 %, or equivalently an increase in costs of less than 5 %, would be sufficint to change the result from positive to negative. For the large-scale scenario where the net result is negative, an increase in revenue of 7 %, or an 8 % decrese in costs, would be sufficient to change the sign of the net result.

Table 6.1 Financial economic analysis of the biorefinery scenarios.

	Small-scale plant		Large-scale plant	
	Total (DKK/year)	DKK/tonne DM input	Total (DKK/year)	DKK/tonne DM input
Biorefinery				
Costs				
Investment and maintenance costs				
Investment – protein plant	2,744,866	137	16,469,194	110
Maintenance – protein plant	1,000,000	50	6,000,000	40
Investment – biogas plant	530,261	27	28,726,901	192
Maintenance – biogas plant	28,088	1	12,173,328	81
Investment - upgrading	-	-	11,558,974	77
Total investment and maintenance	4,303,214	215	74,928,397	500
Labour costs				
Labour – protein plant	1,800,000	90	7,200,000	48
Labour – biogas plant	300,000	15	5,800,000	39
Total labour	2,100,000	105	13,000,000	87
Biomass input costs				
Grass – compensation to farmers	12,778,575	639	95,858,385	639
Grass – harvesting and transport	6,925,455	346	55,409,325	369
Total biomass input	19,704,030	985	151,267,710	1,008
Taxes	29,951	1	490,767	3
Total costs	26,137,195	1,307	239,686,874	1,598
Revenues				
Sale of products				
Fibre fraction	13,758,003	688	-	-
Protein product	9,455,415	473	70,915,611	473
Digested biomass	569,467	28	16,383,000	109
Biomethane	530,483	27	25,842,756	172
Total sale of products	24,313,367	1,216	113,141,330	754
Subsidies	2,832,420	142	111,456,838	743
Total revenue	27,145,787	1,357	224,598,205	1,497
Net result - biorefinery	1,008,592	50	- 15,088,669	- 101
Public finances				
Expenses - subsidies	2,832,420	142	111,456,838	743
Revenue - taxes	29,951	1	490,767	3
Net result - public finances	- 2,802,470	- 140	- 110,966,071	- 740

Nevertheless, based on Table 6.1 the large-scale biorefinery turns out to represent a net cost to both stakeholders, suggesting that neither of the two have any financial incentive for engaging in biorefinery investments. Thus, the analysis indicates that promoting investments in large-scale biorefineries is not just a question of altering the distribution of costs and revenue among stakeholders. From a financial economic point of view, the challenge is more fundamental in terms of profitability, calling for optimisations of the production processes or novel alternative biorefinery concepts.

Considering the small-scale scenario, the biorefinery returns a net profit to biorefinery owners, but still represents a net cost to the state. This discrepancy suggests that there should be potential for redistributing costs and benefits between the two actors, making it profitable to both. Considering the respective costs and revenues, the loss incurred by the State is almost three times the gain of biorefinery owners. These circumstances lend support to the previous observation, that also for small-scale refineries it will be important to focus on optimization of production processes and developing novel biorefinery concepts.

Considering the individual costs listed in Table 6.1 it appears that total investment costs per unit of input are more than twice as high in the large-scale scenario as in the small-scale scenario, which is somewhat counterintuitive, as one would normally expect economies of scale. Comparing the two scenarios, the economies of scale effect can be observed for investment and operation costs related to the protein plant, but not for investment and maintenance costs related to the biogas part of the biorefinery. However, the biogas related operation and maintenance costs are low in the small-scale scenario mainly due to the assumption that the required processing capacity can be obtained at low or no cost by expansion of the reactor and upgrading capacity at an existing plant.

In case the small-scale scenario will require construction of a new biogas plant, the economies of scale effect is likely to apply, with total investment and maintenance costs per unit of biomass likely to exceed those calculated for the large-scale scenario. In relative terms, total investment and maintenance costs account for approximately 15 % (small-scale) and 30 % (large-scale) of total expenses. For labour and input costs the economies of scale effect apply, but is relatively minor. Tax expenses are three times higher per tonne input in the large-scale scenario than in the small-scale scenario, but as tax payments represents a minor expense in relative terms, this difference has little impact on the overall results of the analysis. In both scenarios biomass input costs is the dominant cost component, accounting for approximately 75 % (small-scale) and 60 % (large-scale) of total expenses, with one third of the biomass related expenses attributed to harvesting and transport, and two thirds to compensation of farmers.

Considering the revenues per unit of input, they are similar for the sale of the protein product, whereas there is some variation between the two scenarios as to the relative importance of other sources of revenue. The primary source of revenue in the small-scale scenario is the fibre fraction for feed, accounting for 51 % of total revenue, while another 39 % stems from remaining products (protein, digested biomass and biomethane). The final 10 % is from subsidies. In contrast, only 50 % of the revenue in the large-scale scenario comes from the sale of products, with the other 50 % a result of subsidies. The analyses clearly show that the financial economic profitability of the large-scale scenario is entirely dependent on the subsidies granted for biogas production. Finally, the relative significance of 1) sale of protein, and 2) sale of biomethane as a share of total revenues amount are 35 % and 2 % in the small-scale scenario, and 32 % and 12 % in the large-scale scenario. Hence, the two main products contribute merely 37 % and 44 % of total revenue in the two scenarios.

7 Welfare economic analysis and results

In this chapter, the profitability of the scenarios will be assessed seen from a welfare economic point of view, i.e. the overall profitability seen from society as such. A project that is desirable seen from the private economic (i.e. financial) perspective of a business owner may not necessarily be desirable seen from a welfare economic point of view, and vice versa.

The most important difference between financial and welfare economic analyses relates to externalities, discounting, the treatment of taxes and subsidies and the price levels used in the analyses. The differences will be described in the following sub-sections.

7.1 Externalities

Welfare economic analysis is based on utility ethics and the notion that resources are scarce. Hence, the goal is to allocate resources in a way that maximizes the aggregate level of utility / welfare in society. The results of a welfare economic analysis can be used to assess whether or not the implementation of a given project leads to a welfare improvement or not compared to the specified baseline. The analysis, however, does not say anything about how the welfare changes are distributed across different segments of society, nor if there are alternative projects, which could lead to larger welfare improvements using the same amount of scarce resources.

While financial economic analysis is restricted to consequences reflected in actual monetary flows between different stakeholders, i.e. costs and revenues, a welfare economic analysis includes all consequences that affect utility, whether or not these consequences are expressed in monetary terms or not. As such welfare economic analysis includes both market and non-market consequences of the project being implemented. Even though the focus of welfare economic analysis is extended beyond the scope of consequences, which impact welfare directly in the form of monetary flows, the unit of assessment is nevertheless money. In this context, one of the key challenges when conducting welfare economic analysis of projects with environmental implications relates to the assessment of external non-market consequences in monetary terms. There are several different approaches, which can be used, but common for all are that they introduce an extra element of uncertainty in the analysis. Thus, not only the assessment of the consequences as such, but also the translation of the welfare impacts of the consequences into monetary units, are bound to be associated with some degree of uncertainty.

Ideally, welfare economic analysis should encompass all welfare changes induced by the project, independent of who experience the changes. In practice, however, the analyses in Denmark are most often limited to consider welfare changes occurring within a national context. Extending the scope beyond national borders is complicated due to difficulties associated with predicting what the consequences will be, how they will affect welfare, and what the monetary value of the welfare changes will be. Hence, the inclusion of consequences outside national borders is often restricted to a qualitative description of potentially significant consequences.

7.2 Taxes and subsidies

Taxes and subsidies represent transfers between different actors. They do not decrease / increase utility as such; instead, they represent a redistribution among different actors[33]. Seen from a welfare economic point of view, it is the sum of all utility that matters; how the utility is distributed between different stakeholders is not the prime concern. Hence, seen from the welfare economic perspective the prime goal is to maximize utility in society, and once this is obtained, a secondary goal can be to ensure a fair and / or suitable distribution of this utility. With reference to this line of reasoning, tax and subsidy payments are not included in welfare economic analysis as direct costs and revenues.

However, changes in tax revenue and subsidy expenses may indirectly affect the welfare economic profitability of projects. Assuming that other public activities are unaffected by the implementation of the considered project, any net change in public income caused by implementation of the project will have to be off-set by either tax increases or decreases depending on whether there is a decrease or increase in public income. The imposition of taxes is considered to cause a welfare economic loss, as it introduces a discrepancy between the marginal social cost and benefit of the good or service, which is being taxed. The welfare economic loss of increasing taxes is called a deadweight loss or tax distortion loss, representing an actual loss of utility that needs to be accounted for in the welfare economic analysis. According to the Danish Ministry of Finance (2017), the tax distortion factor is estimated to 1.1, implying that an increase in tax bills triggers a tax distortion loss equivalent to 10 % of the amount collected.

7.3 Price level and discount rate

While financial economic analysis is based on factor prices, welfare economic analysis is based on market prices, which are prices including taxes and subsidies. Market prices are the prices that face consumers, and they reflect the utility associated with consuming the considered goods and services. The adjustment from factor to market prices is done with the socalled ‘net charging factor’, which reflects the share of private consumption comprised by indirect taxes and subsidies. The net charging factor is estimated to 1,28 (Finansministeriet, 2019), and conversion from factor prices to market prices is done by multiplying factor prices by the net charging factor.

The discount rate for use in welfare economic analysis as recommended by the Danish Ministry of Finance is 4 % for the first 35 years, declining to 3 % and then to 2 % after 70 years (Finansministeriet, 2017). This discount rate is lower than the one used in the financial economic analysis, whereby costs and benefits arising into the future weigh substantially more in the welfare economic analysis. The use of a lower discount rate in the welfare economic analysis means that the required rate of return on investment is less when seen from the perspective of society than when seen from the perspective of private stakeholders. An argument for using different discount rates in financial and welfare economic analysis relates to the difference between utility discounting and consumption discounting. Seen from the perspective of the individual

[33] This may be illustrated by looking at the subsidies granted for upgraded biogas. While these subsidies represent a benefit for the biorefinery owners, they represents an expense for the State. The revenue and the expenses are of the exact same magnitude implying that they cancel out when adopting the perspective of society at large.

person or investor, the relevant discount rate is likely to include elements of both types of discounting. Seen from the perspective of society, however, it may be difficult to justify utility discounting, as this would favor current generations over future generations. Accordingly, the appropriate discount rate to use in welfare economic analysis should primarily be set to reflect the expected changes in future consumption possibilities.

7.4 Welfare economic profitability of biorefinery scenarios

Table 7.1 presents the welfare economic costs and benefits associated with the biorefinery scenarios. The figures have been adjusted with the net charging factor of 1.28 (see Section 7.3).

Prior to the adjustment with the net charging factor, the investment costs have been rescaled based on the welfare economic discount rate of 4 %. The lower discount rate serves to reduce the estimated annual investment cost, while adjustment by the net charging factor works in the opposite direction by increasing costs.

Comparing the figures in tables 6.1 and 7.1 it appears that the net effect on aggregate investment and maintenance is a cost increase. Taxes and subsidies no longer enter the analysis directly as costs and revenues; instead their welfare economic effect enters the analysis in the form of a tax distortion loss. Since aggregate subsidy payments by far exceed aggregate revenues from taxes, the scenarios have a negative net impact on public finances. The net effect on public finances is 2.8 mDKK in the small-scale scenario and 111 mDKK in the large-scale scenario (see Table 6.1), and to maintain public finances, taxation needs to be increased, entailing a tax distortion loss of 0.36 mDKK and 14.2 mDKK in the small and large-scale scenario respectively (see Table 7.1).

Table 7.1 summarizes the externalities assessed in Chapter 5. The net outcome of including externalities in the analysis is for both scenarios negative, decreasing their welfare economic profitability. Still, it must be noted that only the externalities that can be assessed in economic terms have been included in the analysis, and perhaps more importantly, that the national limitation implies that externalities outside (GHG from soy crops substituted and additional mineral fertilizer production) Denmark are not included.

Table 7.1 Welfare economic consequences of biorefinery scenarios.

	Small-scale plant		Large-scale plant	
	Total (DKK/year)	DKK/tonne DM input	Total (DKK/year)	DKK/tonne DM input
Biorefinery				
Costs				
Investment and maintenance costs				
Investment – protein plant	2,878,115	144	17,268,691	115
Maintenance – protein plant	1,280,000	64	7,680,000	51
Investment – biogas plant	529,091	26	28,663,513	191
Maintenance – biogas plant	35,953	2	15,581,860	104
Investment - upgrading	-	-	12,769,876	85
Total investment and maintenance	4,723,158	236	81,963,941	546
Labour costs				
Labour – protein plant	2,304,000	115	9,216,000	61
Labour – biogas plant	384,000	19	7,424,000	49
Total labour	2,688,000	134	16,640,000	111
Biomass input costs				
Grass – compensation to farmers	16,356,576	818	122,698,733	818
Grass – harvesting and transport	8,864,582	443	70,923,936	473
Total biomass input	25,221,158	1,261	193,622,669	1,291
Total monetary costs	32,632,317	1,632	292,226,610	1,948
Revenues				
Sale of products				
Fibre fraction	17,610,243	881	-	-
Protein product	12,102,931	605	90,771,983	605
Digested biomass	728,917	36	20,970,240	140
Biomethane	679,018	34	33,078,728	221
Total sale of products	31,121,110	1,556	144,820,950	965
Total monetary revenue	31,121,110	1,556	144,820,950	965
Tax distortion loss	358,716	18	14,203,657	95
External costs				
GHG emissions	- 212,895	- 11	5,753,981	38
Air pollution	- 28,865	- 1	- 652,685	- 4
N leaching	409,850	20	- 6,727,000	- 45
P leaching	68,851	3	517,229	3
Ammonia emissions	- 247,350	- 12	- 1,848,750	- 12
Cadmium	- 61,069	- 3	- 458,048	- 3
Non-road transport (field work)	39,436	2	295,791	2
Road transport	- 207,441	- 10	- 3,111,825	- 21
Total external costs	- 239,483	- 12	- 6,231,306	- 42
Net welfare economic result	**- 2,109,406**	**- 105**	**- 167,840,623**	**- 1,119**
Ammonia emissions, additional external costs with continued non-attainment of reduction target for Denmark	- 1,207,650	- 60	- 9,026,250	- 60
Gross welfare economic result including non-domestic ammonia damages	- 3,317,056	- 166	- 176,866,873	- 1,179

The third row from the bottom of Table 7.1 shows that the net welfare economic results is negative for both scenarios, although the magnitude of the deficit differs markedly. The actual loss per tonne of biomass input differs significantly between the two scenarios. The results suggest that biorefinery production according to the specific scenarios defined in this analysis is not desirable seen from a welfare economic point of view.

It becomes clear from closer inspection of tables 6.1 and 7.1 that while absolute costs increase due to the adjustment from factor prices to market prices, the relative significance of the different cost components remains comparable. In both scenarios biomass input costs continue to represent the largest cost component, accounting for 77 % (small-scale) and 66 % (large-scale) of total costs. Investment and maintenance costs account for 14 % (small-scale) and 28 % (large-scale) of costs, while the remaining 8 % (small-scale) and 6 % (large-scale) of costs can be attributed to labour. This pattern clearly shows that biomass input costs constitute the most critical cost component to biorefinery profitability.

Considering the revenues, and contrasting tables 6.1 and 7.1, the fact that in the welfare economic analysis subsidies no longer enter the analysis has a large negative impact on results, particularly for the large-scale scenario where 50 % of the financial economic income stems from subsidies. In the small-scale scenario, where the share of subsidies was minor (10 %), the relative significance of the different revenue components has not changed dramatically; revenue from the sale of fibre fraction, protein product, digested biomass and biomethane now account for 57 %, 39 %, 2 % and 2 %, respectively. In the large-scale scenario, on the other hand, the relative significance of the different revenue components has changed significantly; income from sale of protein product account for 63 % of total welfare economic revenue, while 14 % and 23 % of income can be attributed to sale of digested biomass and biomethane. Thus, while sale of the fibre fraction represents the most important source of income in the small-scale scenario in both the financial and welfare economic analyses, the most important source of income in the large-scale scenario changes from being subsidies to being sale of the protein product when shifting the perspective from a financial to a welfare economic perspective.

The externalities represent a net welfare economic loss in both scenarios although the magnitude of the loss differs, the loss in the large-scale scenario being more than three times as large as the one in the small-scale scenario. Increased ammonia emissions, attributable to increased use of fertilizer, result in an external cost of 12 DKK / ton DM. The increased use of fertilizer involves an external cost related to cadmium of limited magnitude. The scenarios are based on highly fertilized grass (450 kg N / ha) as input to protein production; whereby the land use requirement is minimized. However, the intensive use of fertilizer is associated with external costs, as becomes clear when we move from the financial analysis to the welfare economic. Increases in road transport and biorefinery air pollutants provide further external costs, although 2-4 times greater in the large-scale scenario. On the positive side, P leaching and use of diesel for fieldwork diminish in both scenarios, providing positive external impacts. The sign of the net external impact from changes in N leaching and GHG emissions varies across scenarios. In the small-scale scenario there is a positive net impact from changes in N leaching, while the impact from changes in GHG emissions is negative. For the large-scale scenario the reults are opposite. Overall, the conclusion for both scenarios is that although there are both positive and negative external impacts, the magnitude of the positive effects is not sufficient to offset the negative external effects.

8 Discussion and sensitivity of results

When comparing results of the two scenarios, the differences in profitability are not mainly due to the difference in scale. There are important differences in the underlying assumptions for the two scenarios, e.g. in terms of how the residues from protein production are used. The assumption in the small-scale scenario that excess capacity is available from an existing biogas plant is the primary explanation for the differences in investment costs between the two scenarios. Nevertheless, some differences remain related to scale, e.g. the differences in labour costs and protein plant investment costs.

Table 8.1 Net financial and welfare economic results for scenarios.

		Small-scale scenario		Large-scale scenario	
		DKK/tonne DM	DKK (Total)	DKK/tonne DM	DKK (Total)
Financial economic	Biorefinery owners	50	1,008,592	- 101	- 15,088,669
	Public finances	- 140	- 2,802,470	- 740	- 110,966,071
Welfare economic		- 105	- 2,109,406	- 1,119	- 167,840,623

In the present chapter, the sensitivity of the results is investigated for different cost and revenue components. We examine them individually, while in reality, several factors may simultaneously differ, which should be kept in mind.

8.1 Subsidies

It follows from Table 6.1 that subsidies for biogas production are an important source of revenue, particularly in the large-scale scenario, where they provide about 50 % of total revenue. Such subsidies need to be financed by means of taxes, and from a welfare economic perspective, a tax distortion loss is expected (see Table 8.1). For this reason, any changes in subsidy schemes will affect the results of both the financial and welfare economic analyses. As the present subsidy schemes are time limited, it is relevant to consider how changes could influence the outcome of the analysis.

It follows from Section 4.7.2, that the subsidy has three different elements, while also depending on the actual use of the biogas. The temporary price premium of 10 DKK/GJ is being phased out, and will be terminated in 2020. Whether the basic subsidy and the regular price premium will be continued depends on several factors, including the market price of natural gas, changes in the price index, policy-makers' decisions on renewables and guidelines for approval of state aid from the European Commission. The impact of projected changes in the price of natural gas and changes in the price index on the size of subsidies is presented in Table A2.1 in Appendix 2, based on the price index and price projections from Energistyrelsen (2017).

It follows from Table A2.1, that the expected increases in the price of natural gas will cause the price premium of 26 DKK/GJ to be phased out from 2030, reducing biogas support to 30 DKK/GJ respectively 74.1 DKK/GJ for biogas for processing and upgrading. Thus, even with no changes in the current legal framework the income from subsidies is expected to decrease.

To investigate the impact of changing the level of subsidies, the analyses have been adjusted based on the average subsidy level available over the period 2017-2036. Considering the present generous support scheme, combined with the negative welfare economic balance, it has not been considered relevant to investigate an increase.

Assuming that the existing scheme and legal framework will be continued, the average annual subsidy over the twenty-year period (2017-2036) can be calculated to 92.9 and 49.2 DKK / GJ for biogas for upgrading and biogas used for processing respectively. Substituting the 2017 subsidy levels used in the analyses by these average subsidy levels has an impact on results, but the nature and magnitude of the effects varies across scenarios and analyses. When interpreting the outcome, it is important to keep in mind that only the subsidy levels have been changed. As the subsidy levels to some extent depend on the market price of natural gas, it could be argued that the impact of changing subsidy levels should be considered in tandem with the corresponding predictions of changes in the price of natural gas. The impact of changing natural gas prices is investigated in Section 8.3, where also the net effect of support and price changes are considered jointly.

In the small-scale scenario, the change in the level of subsidies reduces the revenue accruing to biorefinery owners by 47 DKK / tonne DM, implying that the net-result is reduced to 3 DKK / tonne DM. Conversely, it has a positive impact on public finances, as the deficit is reduced by a corresponding amount, i.e. 47 DKK / tonne DM; however, there continues to be a significant negative impact on public finances of approximately 93 DKK / tonne DM. The reduced subsidy level implies a decrease in the tax distortion loss of 6 DKK / tonne DM. Thus, it has a positive effect on the welfare economic result, albeit limited.

In the large-scale scenario revenues to biorefinery owners are reduced by 230 DKK / tonne DM, when the subsidy levels are changed from the 2017 level to the average level for the period 2017-2036, while the deficit to public finances is reduced by the same amount. The reduction in the implied tax distortion loss is 29 DKK / tonne DM in the large-scale scenario, and although this correspond to a reduction of approximately 30 % it does not influence the net welfare economic result decisively.

8.2 Fertilizer use for grass cultivation

The use of intensively fertilized grass ensures a high yield per ha, which – all else equal – contributes positively to results, as it minimizes the agricultural area required for cultivation, thereby reducing the economic loss of displacing previous production. However the intensive use of fertilizer implies some costs too –direct expenses for mineral fertilizers, as well as external costs related to ammonia emissions. Hence, it is relevant to investigate the impact of reducing the amount of fertilizer; here focus is on a change from 450 to 300 kg N / ha.

Table 8.2 shows how the average cost for fertilizers[34] will be reduced by 1,110 DKK / ha, while average yield is reduced by 1,848 kg / ha, triggering a need to convert more farmland (about 20 %) to produce the required amount of biorefinery input . The net effect of reduced fertilizer use and increase in land use

[34] Grass cultivation costs plus the lost contribution margin from cereal production. Only the former is affected by the change in fertilizer application. The change is equal to the change in fertilizer application times the price of fertilizer. Here a price of 7.4 DKK / kg N is used.

is an increase in biomass input costs of 9 DKK / tonne DM, corresponding to a welfare economic cost of 12 DKK / tonne DM. Other cost and benefit components will be affected by shifting to moderately fertilized grass.

Table 8.2 Changes in grass input costs following a reduction in fertilizer input[35].

	Small-scale 450 kg N/ha	Large-scale 450 kg N/ha	Small-scale 300 kg N/ha	Large-scale 300 kg N/ha	Difference (450 kg/ha to 300 kg/ha)
Average cost (DKK/ha)	6,358	6,358	5,248	5,248	- 1,110
Average yield (kg/ha)	9,950	9,950	8,102	8,102	- 1,848
No. of ha	2,010	15,075	2,469	18,515	
Total costs (DKK)	12,779,899	95,849,246	12,955,359	97,165,192	
Cost (DKK/tonne DM)	639	639	648	648	9

Transportation costs and the associated external costs, can be expected to increase, as transport distances will be longer, while also the harvesting costs per tonne DM go up with less grass yields per ha.

On the other hand, reductions in N leaching and NH_3 (ammonia) emissions provide positive benefits of reducing fertilizer applications.

With a reduction in fertilizer application from 450 to 300 kg N / ha, NH_3 emissions will be reduced from 9.9 kg / ha to 6.6 kg / ha. Adjusted for the increased land area required for grass cultivation, the gross reduction in NH_3 emissions is approximately 3.6 tonnes in the small-scale scenario and 27 tonnes in the large-scale scenario. This corresponds to a reduction in the external costs of ammonia emissions of approximately 5 DKK / tonne DM. Thus, the reduction in ammonia related external costs is not sufficient to compensate for the additional cost associated with reducing the level of fertilizer application.

Similarly, N leaching from fertilizer applications will be reduced from 47 to 27 kgN / ha, resulting in total reductions of approximately 27 and 201 tonnes N in each of the the scenarios. The value of this reduction is 33 DKK / tonne DM.

The results suggest that a reduction in fertilizer intensity is economically sound, once the perspective is extended beyond the private economic perspective. While the change causes an increase in costs for biorefinery owners due to an increase in input price of 9 DKK / tonne DM, plus the amount by which transport and harvesting costs will increase, the change improves the welfare economic result. Thus, seen from a welfare economic perspective the increase in input costs of 12 DKK / tonne DM will be off-set by the benefits from reductions in ammonia emissions and N leaching, totaling 38 DKK / tonne DM. However, the extent to which this conclusion holds of course depends on how much transportation and harvesting costs (plus the external effects associated with these activities) will increase.

8.3 Output prices

The revenue from product sales account for a significantly greater share of total revenue in the small-scale scenario compared to the large-scale scenario (approximately 90 % compared to approximately 50 % - see Table 6.1). The

[35] Average yield assessed based on crop production data in Appendix 4.

remaining share of revenue is from subsidies. This has implications for the sensitivity of results to changes in output prices.

With regard to the small-scale scenario, where revenues from sale of the fiber fraction represents a main source of income, an 8 % decrease in its sales price suffices to reduce net results to zero. When assessing the value of the fiber fraction (see Section 3.7) transportation costs were not included, and could serve to reduce its value, either by reducing demand or suppressing the market price. Jensen and Gylling (2018) estimate average transportation costs for the fibre fraction, with a distance of 10 km, to 11.12 DKK / tonne DM / km. Using their estimate and a similar distance, the value of the fibre fraction is reduced by 1,548,929 DKK[36], equivalent to a reduction in revenue of 77 DKK / tonne DM input. A reduction of this magnitude would be sufficient to turn the net result to biorefinery owners negative, underlining that the result for the small-scale scenario is sensitive to price changes related to the fibre fraction.

The value of the protein product is assessed with reference to the price of conventional soy meal, based on a soy price of 271 DKK / hkg. Unless the feeding value of the protein product turns out to be lower than that of soy, there is no reason to believe that the price of the protein product should be lower than the price of soy. Still, fluctuations in the soy price may influence the revenues from protein sales. During a 10 year period (2007-2016) the price of soy has varied between 151 DKK / hkg (2007) and 319 DKK / hkg (2013), suggesting that variations in the sales price of the protein product represents a potentially important source of uncertainty. On average, however, the soy price has been 250 DKK / hkg (current prices), corresponding to a revenue from protein sales of 436 DKK / tonne DM, which is close to the figure of 473 DKK / tonne DM used in the analysis.

Considering that the protein product represents a locally (i.e. nationally) produced product, and that it is GMO-free, there is a possibility, that it might be sold at a higher price compared to conventional soy. Jensen and Gylling (2018) indicate a price of GMO-soy of 250 DKK / hkg, and list prices of non-GMO soy and organic soy to be respectively 365 DKK / hkg and 535 DKK / hkg. Applying the non-GMO price of 365 DKK / hkg the value of the protein product in our scenarios would increase by 164 DKK to 637 DKK / tonne DM, significantly improving the net result of the scenarios (214 DKK / tonne DM and 63 DKK / tonne DM for the small and large-scale scenarios, respectively). This suggests that marketing efforts directed at highlighting more intangible, and not directly nutritionally related, characteristics of the product could be relevant to consider.

Revenue from sales of the digested biomass accounts for approximately 2 % and 7 % of total revenue in the scenarios, and the revenues from sale of biomethane are of a similar magnitude, accounting for 2 % and 12 %, respectively. Thus, in relative terms both product represents minor revenue components, especially in the small-scale scenario where the two products jointly account for merely 4 % of total revenue.

The value of the digested biomass is based on the price of N, P and K in mineral fertilizers. In the past five years (2013-2017) the average price of N, P and

[36] Calculated as follows: 41,333 tonnes * 0.337 tonnes DM / tonne * 11.12 DKK / tonne / km * 10 km)

K has been 7.73, 12.4 and 4.7 DKK/kg, which corresponds well with the prices used in the analyses (7.4, 12 and 5 DKK/kg). While fertilizer prices might not represent a major source of uncertainty, an underlying assumption for the assessment of the value of the digested biomass is that farmers will be indifferent between using digested biomass and mineral fertilisers. Still, some farmers could find it less flexible and more burdensome to use a combination of synthetic fertilizer and digested biomass. In that case it is likely that farmers would need an economic incentive (e.g. a cost saving) to opt for using digested biomass, which could suppress the price relative to its actual nutrient content. Hence, the value of the digested biomass might be overestimated in the analysis, and adjusting the value downward will have a relatively larger impact on the large-scale scenario than on the small-scale scenario, as the proportion of revenue from sale of digested biomass is significantly larger in the former.

The value of biomethane is assessed with reference to a price of natural gas of 38 DKK/GJ. Projections from Energistyrelsen (2017) indicate that the price of natural gas is expected to increase to 75 DKK/GJ by 2036 (See Table A2.1 in Appendix 2), while the average price over the 20-year period is 56 DKK/GJ. Changing the price used to assess the value of biomethane in the analysis to the average price over the 20 year period (equivalent to the investment lifetime of the biorefinery) will increase the revenue from biomethane sales significantly. In the small-scale scenario, the revenue from biomethane will increase by 12 and 15 DKK/tonne DM (in the financial and welfare economic analyses, respectively), and in the large-scale scenario it will increase by 82 and 105 DKK/tonne DM (in the financial and welfare economic analyses, respectively). Despite the improvement from the increase in the price of natural gas, net revenues will be offset by implications in relation to subsidies. Firstly, the 26 DKK/GJ price premium is lowered corresponding to the natural gas price increases. Secondly, the remaining subsidies (of 79 DKK/GJ and 39 DKK/GJ) will despite some indexation nevertheless lose value due to inflation. Thirdly the temporary 10 DKK/GJ subsidy will be phased out. Thus, the net effect of increasing the price of natural gas to the average for the period 2017-2036 and reducing subsidies to the average level for the same period will be a loss in incomes to biorefinery owners. The net loss amounts to 35 DKK/tonne DM (i.e. 12-47 DKK/tonne DM) in the small-scale scenario and 148 DKK/tonne DM (i.e. 82-230 DKK/tonne DM) in the large-scale scenario. Changing the price of natural gas to the 75 DKK/GJ projected for 2036, the financial economic revenue accruing to biorefinery owners from sale of biomethane will increase by 25 and 168 DKK/tonne DM, which – assuming that the subsidy levels are at the level estimated for 2036 - is not enough to compensate for the revenue erosion from reductions in effective subsidies (76 and 372 DKK/tonne DM for the small and large-scale scenarios respectively). If however the fixed subsidies (other than 26 DKK/GJ price premium) are maintained at their current effective level (2017), the decrease in subsidy revenue caused by an increase in the price of natural gas to 75 DKK/GJ will be significantly less. For the small-scale scenario revenue will decrease by 49 DKK/tonne DM and for the large-scale scenario it will decrease by 237 DKK/tonne DM; both changes, however, are numerically larger than the respective increases in revenue brought about by the higher price on natural gas implying that the net effect remains negative.

Up to now we have considered changes in the prices of the produced products, but a perhaps equally important aspect is the potential for other products than the ones considered here, preferably high-value products (e.g. for human consumption), where production can be integrated with the production of green protein and biogas. Thus, if innovation efforts are successful, it could have an impact on the profitability of biorefinery production, both seen from a private economic and a welfare economic point of view. Potentially, it could help diminish the need for subsidies. Currently, however, the analysis shows that considerable financial support from taxpayers is a prerequisite for making the considered biorefinery scenarios attractive seen from a private economic point of view.

8.4 Biomass input prices

Expenses for biomass input is the most significant cost item, with two different components – compensation to farmers, and harvest and transportation costs.

The former is assessed with reference to the lost contribution margin from cereal cultivation plus the grass cultivation costs (excl. harvest and transport), and it is affected by input prices (seeds, fertilisers, labour and machinery) and cereal prices. Table 8.3 presents the input prices applied in the analysis, compared with the corresponding prices assessed as five-year averages (2013-2017). For fertilizer, seed and cereal prices, there do not seem to be any significant differences between the prices used in the analyses, and the five-year averages. For machine and labour costs, on the other hand, there are more pronounced differences to the five-year averages. For spring barley the difference is 216 DKK / ha while it is 372 DKK / ha for winter wheat; on average the difference is 294 DKK / ha. Recalculating the compensation to farmers based on the five-year average machine and labour costs of cereal production, the required compensation is reduced by approximately 30 DKK / tonnes DM – which, for the large-scale scenario serves to reduce the financial economic net loss by 30%. However, it must be noted that the difference is unrelated to price changes as such, but rather stems from differences in the number of pesticide applications, with less applications required in the five-year period than in the reference year.

Table 8.3 Input and output prices: comparison of 2017 prices and 5-year averages.

	Price used in analyses	Average price 2013-2017
Fertiliser DKK/kg (N/P/K)	7.4/12/5	7.7/12.4/4.7
Seed – DKK/kg (Spring barley/Winter wheat/Grass)	2.7/2.6/37.5	2.7/2.6/37.2
Machine and labour costs – DKK/ha (Spring barley/Winter wheat)	4,705/5,621	4,489/5,249
Cereal prices - DKK/kg (Spring barley/Winter wheat)	1.08/1.16	1.16/1.19

The second component of input prices, i.e. harvest and transportation costs, has been considered based on detailed calculations of the two scenarios (Claus Grøn Sørensen, personal communication 2017). The cost estimates are derived from an optimized harvest and transportation system, which could be difficult to accomplish in practice. For the small-scale scenario, where the net-result is positive, an increase in harvest and transportation costs of approximately 15 % would be sufficient to change the sign of the net result.

8.5 External effects

Estimates of external costs are associated with significant uncertainties. They stem from issues associated with quantifying the environmental impacts in physical terms as well as with estimating the monetary values. The relative contribution of external impacts to the overall net result, however, implies that major changes in the valuation of externalities need to occur, to have any real impact on the welfare economic results. This conclusion especially applies to the large-scale scenario, where the net welfare economic loss is approximately ten times higher than in the small-scale scenario.

In both scenarios, the external costs of increased ammonia emissions represent a significant externality. There are two opposing components; ammonia emissions increase from increased use of mineral fertilizer, while they diminish due to less crop residue leftovers on the fields (cf. Section 5.5). The increase in ammonia emissions could be mitigated by less fertilizer intensive cultivation of grass. The net effect of a 33 % reduction in the level of fertilizer was shown in Section 8.2 to reduce external costs by approximately 5 DKK/tonne, which although representing a significant reduction in ammonia related external cost (around 40%), has a minor impact on the overall welfare economic profitability of the scenarios.

In both scenarios the external effects related to air pollution, P leaching, cadmium and non-road transport all have a quite small impact both on the net value of external effects, and the net results of the scenarios as such. Accordingly, it is not considered relevant to investigate how changes in the underlying assumptions regarding these effects affects the outcome of the analyses. Increases in road transport represents one of the significant negative external impacts, but compared to the overall net-result they play a minor role. Whether it is possible to reduce the negative impacts from road transport depends on several factors, e.g. transport distance, lorry capacity and fuel efficiency.

While within the ETS the future price of CO_2 emissions allowances is associated with significant uncertainty, there are several different approaches to assessing the value of changes in greenhouse gases (GHG) outside the ETS. It is recommended to conduct sensitivity analyses if the ETS and non-ETS prices are considered critical in determining the overall profitability of a project (Energistyrelsen, 2017). However, in the present analysis the monetary value of domestic GHG emissions is not seen to be critical. Still, to illustrate the significance of changes in the value of GHG emissions, the external costs of the GHG emissions considered in Section 5.1.5[37] are recalculated using a value of 1,000 DKK/tonne CO_2 equivalent. This is the upper-bound value recommended in Energistyrelsen (2017) for sensitivity analyses concerning non-ETS emissions. If the price is only changed for the non-ETS emission, the external cost of GHG emissions increases by 39 DKK/tonne DM in the small-scale scenario, while the net external benefit from changes in GHG emissions is reduced by 36 DKK/tonne DM in the large-scale scenario. If the price of 1,000 DKK/ tonne CO_2 equivalent is applied for all emissions, i.e. also those under

[37] The GHG emissions assessed in Section 5.1.5 only account for some of the GHG emissions changes associated with the scenarios, as there are also GHG emissions associated with transport. It is, however complicated to change the CO_2 price used in the calculations of the external costs of transport, and accordingly the sensitivity of these results to changes in the CO_2 price will not be investigated. With reference to the limited magnitude of total transport related external costs, changes in the CO_2-price are not critical for the results.

the ETS, the net value of changes in GHG emissions becomes -19 DKK / tonne DM in the small-scale scenario and 206 DKK / tonne DM in the large-scale scenario. The different signs of the results for the large-scale scenario is caused by the fact that changes in GHG emissions covered by the ETS are positive (i.e. emissions are reduced) while changes outside the ETS are negative (i.e. emissions are increased).

8.6 Investment, maintenance and labour

All investment, maintenance and labour cost estimates are associated with significant uncertainties. With regard to the protein plant there is currently no commercial production, implying that there is no reference to compare the estimates against. The estimates have been obtained by scaling from the one and only pilot plant, with some adjustment for the expected economies of scale. Investment, maintenance and labour costs related to the protein plant jointly account for 22 % of total financial economic costs (277 DKK / tonne DM) in the small-scale scenario and 13 % (198 DKK / tonne DM) in the large-scale scenario. This implies that an overall reduction in protein plant investment, maintenance and labour costs of around 50% would be required to ensure break-even in the large-scale scenario for biorefinery owners. For the small-scale scenario in contrast, the aggregate investment, maintenance and labour costs related to the protein plant would have to increase by around 20 % to offset the net positive result. In the absence of relevant references, it is not possible to judge whether the cost estimates are representing under- or over-estimations of true costs.

For biogas production and upgrading, numerous references provide estimates of investment, maintenance and labour costs, but significant uncertainties nevertheless persist. Costs vary depending on the specific configuration of the plant in question – e.g. location, type of biomass input, capacity, the technical configuration and how the biogas is to be used. The biogas related investments, maintenance and labour costs differ significantly between the two scenarios owing to the assumption that only the small-scale scenario can take advantage of excess capacity. Aggregate biogas and upgrading related investment, maintenance and labour costs amount to 43 DKK / tonne DM (equivalent to 3 % of total costs) in the small-scale scenario, while it amounts to 389 DKK / tonne DM – corresponding to 24 % of total costs – in the large-scale scenario. Should it not be possible to locate the biorefinery in the vicinity of an existing biogas plant, and it becomes necessary to construct a new biogas plant (including upgrading unit), the biogas related investment costs per unit input are likely to be higher in the small-scale scenario than in the large. Setting the biogas related investment and maintenance costs in the small-scale scenario equal to those calculated for the large-scale scenario, the net-result is decreased by 322 DKK / tonne DM, resulting in a significant deficit for biorefinery owners; and the deficit in the small-scale scenario will then by far exceed that of the large-scale scenario. If the assumption of siting with an existing biogas plant is fulfilled, but it turns out that further modifications are required, the results suggest that annual investment costs can almost double before the net result turns negative.

The annualization of investments is based on an interest rate of 7 % in the financial analysis. Some recent joint biogas plant prospectuses have advertised rates of return of up to 10 %, with a view to attract individual farmers. In contrast, the currently modest interest rates suggest that investors could be attracted at lower rates. Calculations for the small-scale scenario show that reducing the interest rate to 4 % causes a reduction in total investment costs of 31 DKK/tonne DM, while an increase to 10 % causes an increase of 33 DKK/tonne. For the large-scale scenario, the corresponding reduction and increase is -73 and 79 DKK/tonne DM. Thus, changing the interest rate does have an impact, but the considered reduction to 4 % does not have the power to change the net result to biorefinery owners in the large-scale scenario from negative to positive. In order to reach break-even the interest has to be reduced to around 2 %.

Finally, some uncertainties are related to operating the two plants in a joint biorefinery (see Sections 3.3 and 4.4), as some synergies in labour demand are expected. As labour costs account for a relatively small share of total costs any inconsistencies in the analysis in this regard are not expected to impact decisively on results.

8.7 Spatial limits to the analysis

Environmental impacts occurring outside the domestic context are not included, which is a conventional approach prescribed for welfare economic cost benefit analyses in Denmark (Finansministeriet, 2017). In some cases, however, strictly adhering to the domestic perspective can have important implications, as significant environmental consequences – either positive or negative – could be disregarded.

One such case is grass based production of green protein in Denmark. GHG emissions related to imported soy are no doubt significant, and substitution of imported soy with nationally produced green protein offers the opportunity for a reduction in global GHG emissions.

According to Concito (2014) GHG emissions associated with import of 1 kg soy meal are 3.8 kg CO_2 equivalents, and based on an annual net import of soy meal of 1.5 million tonnes the Danish import of soy meal accounts for 6 million tonnes CO_2 equivalents annually. These figures suggest an important positive climate related impact associated with grass based green protein production, which potentially could improve the welfare economic profitability of both scenarios. Applying an updated GHG reduction estimate of 4.2 kg CO_2 equivalents/kg soy meal (Mogensen et al., 2018: 116) in our analysis shows that substituting soy protein with domestic grass protein, could supplant annual GHG emissions by 14,655 tonnes CO_2 equivalents in the small-scale scenario and 109,905 tonnes CO_2 equivalents in the large-scale scenario.

However, predicting what will happen in South America in response to reduced demand for soy meal from Danish farmers is difficult. Questions about verification of the potential GHG reductions are key, as increasing demand in the world market might offset reduced imports of soy. Pricing soy GHGs with an ETS derived price would change the outcome of the economic analysis, but could be considered misleading, as the reductions fall outside national and EU commitments. Third world certified emissions reductions (CER) trade currently at about €0.25/ tonne CO_2 equivalents. From 2020, they are no longer valid for compliance in the EU allowance market, a restriction introduced due to the excess amount of emissions allowances (there is however an emerging market in Asia, e.g. under Korea's ETS). Still, the bio-refinery project would not produce any certified allowances.

Moreover, the intensive fertilization of grass will require import of additional mineral fertilizers with a negative global GHG footprint. Based on a production phase CO_2 footprint of 4.9 kg CO_2 equivalents / kg fertilizer N for calcium ammonium nitrate (Hasler et al., 2017:537), as most commonly used by farmers (Nielsen et al., 2019: 367), the non-domestic fertilizer related GHG emissions for the small and large-scale scenarios are 2,800 and 21,200 tonnes CO_2 equivalents respectively. Imports come from other EU countries as well as from the rest of the world (notably Russia), usually on a 50 / 50 basis, and in the latter case their associated GHG is not internalized with EU emissions trading. Increased GHG emissions in Russia triggered by Danish grass protein production have greater certainty, but under the current guidelines for socio-economic analysis they are not to be included in a welfare economic assessment.

Many different sources of uncertainty have the potential to affect results in either a positive or a negative direction. The impact of changed assumptions on net-result are investigated one factor at the time, while in reality several factors may simultaneously differ from the levels assumed in the analyses. Simultaneous changes in two or more factors may either serve to increase the net-effect (if working in the same direction), or diminish the net effect (if working in opposite directions).

In terms of the welfare economic analyses, the magnitude of the net result for the large-scale scenario implies that major changes are necessary to change the sign of the result, and none of the considered changes have been sufficient to do so. This suggests that the conclusion regarding the welfare economic profitability is quite robust.

9 Conclusions and perspectives

The report contains financial and welfare economic analyses of two different scenarios for green protein production: a small-scale scenario and a large-scale scenario. In both scenarios, intensively fertilized grass supply the input for protein production, and in both scenarios protein production is combined with biogas production. Some of the biogas is used for producing the energy required for processing at the biorefineries, while the remaining part is upgraded to biomethane and fed into the natural gas grid. The processing capacity of the protein plant in the small-scale scenario is 20,000 tonnes DM / year, while it is 150,000 tonnes / year in the large-scale scenario. Apart from the processing capacities, the main distinguishing factor between the two scenarios relates to the use of residues from protein production and provision of biogas production facilities. In the large-scale scenario, both residue fractions (i.e. juice and fibre) are used for biogas production, and the scenario involves the construction of a new biogas plant (including biogas upgrading facilities). In the small-scale scenario, only the juice fraction is used for biogas production, as the fibre fraction is assumed to be used for cattle feed, while it is assumed that the required biogas processing capacity can be obtained by taking advantage of excess capacity at an existing biogas plant.

The financial economic analysis shows that the small-scale biorefinery can return a positive net result to biorefinery owners of 1 mDKK annually, while the large-scale biorefinery returns a negative net result to biorefinery owners of 15.1 mDKK. These net results correspond to a profit of 50 DKK / tonne DM grass input to biorefinery production in the small-scale scenario, and a deficit of 101 DKK / tonne DM grass input to biorefinery production in the large-scale scenario.

In terms of public finances, both scenarios are seen to have negative impacts, while the relative magnitude differs substantially. The negative effect on public finances is due to the generous subsidies for biogas production, combined with reduced, almost negligible, tax rates for biogas use at the biorefinery. The need for public financial support is not per se a reason to caution against combined green protein and biogas production from society's point of view. Externalities are absent from the financial economic analysis, and their internalization could help render the project worthwhile from a welfare economic point of view. However, the results of the welfare economic analysis suggests that this is not the case, as the net outcomes are negative. In both scenarios the negative external effects exceed the positive external effects. While the small-scale scenario performs somewhat better than the large-scale scenario, the analysis has not been able to substantiate expectations for net positive environmental impacts.

More specifically, the net value of external effects is found to be fairly similar across the two scenarios ranging from - 12 DKK / tonne DM in the small-scale scenario to - 42 DKK / tonne DM in the large-scale scenario. Seen from a strict public finance perspective, the desirability of combined green protein and biogas production could be improved by reducing – or abolishing – the subsidization of biogas production. Doing so, however, would – all else equal – make the scenarios unattractive for biorefinery owners, and it would only have a minor impact on the overall welfare economic profitability of the scenarios, as the tax distortion loss induced by the subsidization only constitute a minor component of total costs.

As mentioned several times throughout the report, many of the estimates entering the analyses are associated with significant uncertainties, and accordingly the results are by no means to be interpreted as definitive evidence of the profitability of green-protein biorefineries. Nevertheless, it will require more than minor changes in the different cost and benefit components to demonstrate net positive welfare economic results for the large-scale scenario, where the net deficit is substantial.

In this connection, it is important to note that not all external effects have been included in the analyses, and that the net effect of external effects therefore potentially only reflects a subset of the actual external effects.

In this context it is important to keep in mind the national scope of the analysis, as the value of external effects outside Denmark is excluded. While the potential reductions of GHG emissions in soy producing countries could be an important benefit of grass based green protein production, much depends on the actual land use changes and the extent to which a reduced demand for soy materializes.

Accordingly, it is complicated to assess what the net effect will be of extending the focus to a global one, and therefore it is difficult to say if changing the delimitation of the analyses will serve to change the sign of the net result.

Finally, before making definite conclusions regarding the desirability of combined green protein and biogas production, it is important to note that there may be other motives, e.g. attainment of more long terms political goals, which may be used to justify the implementation of combined green protein and biogas production. Accordingly, as an element of a more long term strategy, and based on expectations that the welfare economic value of the technology will become positive once it matures and/or the societal setting changes, it may be considered welfare economically justifiable to invest in technologies that in their early stages of development give rise to significant welfare economic losses.

Results show that the small-scale scenario performs better than the large-scale scenario – both seen from a financial economic and a welfare economic perspective. This suggests that the scenario set-up considered in the small-scale scenario is the most relevant to pursue, if deciding to proceed with green protein production at commercial scale. In this connection, however, it is important to bear in mind the preconditions that need to be met in order for the small-scale scenario set-up to be relevant. For one, there is a need for an existing biogas plant with excess capacity that the protein plant can be established in connection with. Secondly, the number of cattle in the immediate vicinity of the biorefinery needs to be sufficient to ensure that there is a market for the fibre fraction.

Overall the results of the analyses suggest, that combined green protein and biogas biorefineries are unprofitable both seen from a welfare economic and a public finance perspective. However, the profitability to biorefinery owners is close to break-even, implying that even relatively minor changes may serve to change the result from positive to negative (and vice versa). Whether these results will change over time is difficult to predict, just as it is difficult to predict if the potential changes will affect results in a positive or a negative direction. The economic results might be improved in several ways – i.e. by focusing on reducing costs, increasing revenue and efficiency, minimizing negative external effects, and promoting positive external effects. Considering the early stage of technological development – i.e. the fact that protein production currently only takes place at pilot scale – it seems likely that there is room for technological developments that may serve to either increase the efficiency of production or lower the investment costs. In addition, there may be numerous possibilities for devising new uses of the residues from protein production, e.g. for production of more high value products that may serve to increase the revenue for the biorefinery. Finally, if increased focus is directed at the external effects of the biorefinery production, the welfare economic desirability of green biorefinery production may also be increased. As an example, the analyses has shown that explicit consideration of the external effects of N fertilization may help identify and address potential discrepancies between what is optimal seen from a private economic point of view and what is optimal seen from a welfare economic point of view.

Summing up, the overall conclusions to be drawn from the analyses are that green biorefineries, according to the set-ups defined here, may be profitable to biorefinery owners, but that the net result is likely to be fairly close to break-even. Moreover, the results clearly show that the current level of subsidies for biogas production is a prerequisite for the private economic profitability, while it results in significant public expenditures. As shown in the welfare economic analyses this public expenditure translates into a tax distortion loss of 18 to 95 DKK/tonne DM depending on the scenario. Seen from a welfare economic point of view, both scenarios result in a welfare economic loss, and the magnitude of these losses suggests, that they do not merely stem from minor uncertainties in the cost and revenue estimates - particularly not so for the large-scale scenario.

References

Andersen, M.S., Rasmussen, L.M.F. og Brandt, J. 2019a: Miljøøkonomiske beregningspriser for emissioner 3.0. Notat fra DCE – Nationalt Center for Miljø og Energi, Aarhus Universitet. Available from: https://dce.au.dk/fileadmin/dce.au.dk/Udgivelser/Notater_2018/Miljoeoekonomiske_beregningspriser_for_emissioner_2.0.pdf

Andersen, M.S., Levin, G. and Odgaard, A.V. 2019b: Economic benefits of reducing agricultural N losses to coastal waters for seaside recreation and real estate value in Denmark, Marine Pollution Bulletin 140, 146-156.

Andersen, M.S. 2016: Kortlægning af afgifter på energi m.v. Implikationer for vandselskabernes energi- og ressourceudnyttelse. Notat fra DCE – Nationalt Center for Miljø og Energi, Aarhus Universitet. Available from: http://dce.au.dk/fileadmin/dce.au.dk/Udgivelser/Notater_2016/DCE_Notat_Energiafgifter_mv.pdf

Andersen, M.S. & Brandt, J. 2014: Miljøøkonomiske beregningspriser for emissioner. Notat fra DCE - Nationalt Center for Miljø og Energi, December 2014. Aarhus Univertistet. Available from: http://dce.au.dk/fileadmin/dce.au.dk/Udgivelser/Notater_2014/Miljoeoekonomiske_beregningspriser_for_emissioner.pdf

Birkmose, T., Hjort-Gregersen, K., Hinge, J. & Hørfarter, R. 2015: Kortlægning af hensigtsmæssig lokalisering af nye biogasanlæg i Danmark. Udpegning af områder med særlige muligheder for biogasanlæg. Rapport udarbejdet for Biogasrejseholdet, Erhvervsstyrelsen af SEGES og AgroTech. Available from: https://www.landbrugsinfo.dk/Oekologi/biogas/Sider/Rapport_om_hensigtsmaessig_placering_af_biogasanlaeg_i_Danmark_pl_16_2793_b1.pdf

Concito, 2014: Klimagevinster ved øget proteinproduktion i Danmark. Rapport 27. Januar 2014, Concito. Available from: https://concito.dk/udgivelser/klimagevinster-ved-oget-proteinproduktion-danmark

Cong, R.-G. & Termansen, M. 2016: A bio-economic analysis of a sustainable agricultural transition using green biorefinery. Science of the Total Environment 571(2016):153-163. Available from: https://doi.org/10.1016/j.scitotenv.2016.07.137

COWI, 2013: Business case for biogasanlæg med afsætning til naturgasnettet. Biogas Taskforce, Oktober 2013. Available from: https://ens.dk/sites/ens.dk/files/Bioenergi/business_case_for_biogasanlaeg_med_afsaetning_til_naturgasnettet-09_10_13.pdf

Danish Energy Agency, 2017: Technology Data for Renewable Fuels. June 2017; latest update March 2018. Available from: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_for_renewable_fuels_-_march_2018.pdf

Danish Energy Agency (2015): Technology Data for Energy Plants. Generation of electricity and district heating, energy storage and energy carrier generation and conversion, May 2012. Certain updates made October 2013, January 2014 and March 2015. Available from:
https://ens.dk/sites/ens.dk/files/Analyser/technologydata_for_energy_plants_-_may_2012._updated_2015_ver_nov2017.pdf

Ea Energianalyse, 2014: Anvendelse af biogas til el- og varmeproduktion. Analyser for Biogas Taskforce. Available from:
https://ens.dk/sites/ens.dk/files/Bioenergi/anvendelse_af_biogas_til_el_og_varme_2.pdf

Ellegaard, L. 2015: Notat vedr. omkostning for udvidet udrådningskapacitet (Bilag 11.1). In: Møller, H.B., Nielsen, K.J. (2015): Udvikling og effektivisering af biogasproduktionen i Danmark. Faglig rapport. Biogas Taskforce. Available from:
https://ens.dk/sites/ens.dk/files/Bioenergi/02.02.2016_slutrapport_taskforce_faglig_del.pdf

Energistyrelsen, 2017: Samfundsøkonomiske beregningsforudsætninger for energipriser og emissioner, maj 2017. Energistyrelsen. Available from: https://ens.dk/sites/ens.dk/files/Analyser/samfundsoekonomiske_beregningsforudsaetninger_2017.pdf

Energistyrelsen, 2016: Effekt af biogasproduktion på drivhusgasemissioner, Notat. Available from: https://ens.dk/sites/ens.dk/files/Bioenergi/drivhusgas-effekt_af_biogas_4_okt_2016.pdf

Energistyrelsen, 2014: Teknologivurdering af udvalgte energiteknologier. Nr. 2 (2014): Biogas og biogas-opgradering. Available from:
https://ens.dk/sites/ens.dk/files/Forskning_og_udvikling/teknologivurdering_biogas_og_opgradering_2014.pdf

Finansministeriet, 2019: Dokumentationsnotat om opgørelse af nettoafgiftsfaktoren. 26. April 2019. Available from: https://fm.dk/media/10196/dokumentationsnotat-om-opgoerelse-af-nettoafgiftsfaktoren.pdf

Finansministeriet, 2017: Vejledning i samfundsøkonomiske konsekvensvurderinger, August 2017. Available from:
https://www.fm.dk/publikationer/2017/vejledning-i-samfundsoekonomiske-konsekvensvurderinger

Fog, E. & Thierry, A.M. 2016: Er der økonomi i at udvinde protein fra græs gennem bioraffinering? Available from:
https://www.landbrugsinfo.dk/Energi/andre-teknologier/Sider/pl_16_3115_2490.aspx

Gødningsbekendtgørelsen, 2018: Bekendtgørelse nr. 1008 om jordbrugets anvendelse af gødning i planperioden 2018/2019. Kbh: Miljø- og fødevareministeriet.

Hasler, K., Böhring, S., S.W.F. Omta, O. & Olfs, H-W., 2017. Eco-innovations in the German fertilizer supply chain: Impact on the carbon footprint of fertilizers, Plant Soil Environ. 63 (12) 531-544.

Hermansen, J.E., Jørgensen, U., Lærke, P.E., Manevski, K., Boelt, B., Jensen, S.K., Weisbjerg, M.R., Dalsgaard, T.K., Danielsen, M., Asp, T., Amby-Jensen, M., Sørensen, C.A.G., Jensen, M.V., Gylling, M., Lindedam, J., Lübeck, M. & Fog, E. 2017: Green biomass – protein production through bio-refining. DCA Report No. 93. DCA – Danish Centre for Food and Agriculture, Aarhus University. Available from:
http://pure.au.dk/portal/files/110736531/DCArapport093.pdf

Hjort-Gregersen, K. 2015: Udvikling og effektivisering af biogasproduktionen i Danmark. Økonomi – nøgletal og benchmark. Energistyrelsens Biogas Taskforce. Delrapport 2. Available from:
https://ens.dk/sites/ens.dk/files/Bioenergi/oekonomirapport_udvikling_og_effektivisering_final.pdf

Jacobsen, B.H., Laugesen, F.M., Dubgaard, A. & Bojesen, M. 2013: Biogasproduktion I Danmark – Vurdering af drifts- og samfundsøkonomi. IFRO Rapport Nr. 220. Institut for Fødevare- og Ressourceøkonomi, Københavns Universitet. Available from:
https://naturerhverv.dk/fileadmin/user_upload/NaturErhverv/Filer/Indsatsomraader/Biooekonomi/IFRO_rapport_220.pdf

Jensen, J.D. & Gylling, M. 2018: Økonomiske vurderinger i forhold til værdikæden for Grøn Bioraffinering. IFRO Dokumentation 2018/3, Institut for Fødevare- og Ressourceøkonomi, Københavns Universitet. Available from: http://ifro.ku.dk/publikationer/ifro_serier/dokumentation/

Jensen, L.S. 2015: Udvikling af beregningsmodel til bestemmelse af gødningsværdi og fastsættelse af udnyttelsesprocenter for biomasser til biogasanlæg, Københavns Universitet: Institut for Plante- og Miljøvidenskab.

Jørgensen, P.J. 2009: Biogas – grøn energi. Process, Anlæg, Energiforsyning, Miljø. PlanEnergi. Available from:
http://planenergi.dk/wp-content/uploads/2018/05/9-Biogas_net_dk_tilrettet_version.pdf

Miljøstyrelsen, 2018: Evaluering af den differentierede pesticidafgift. Orientering fra Miljøstyrelsen nr. 26, maj 2018, Miljøstyrelsen, Miljø- og Fødevareministeriet. Available from:
https://www2.mst.dk/Udgiv/publikationer/2018/05/978-87-93710-28-3.pdf

Miljøstyrelsen, 2012: Pesticidbelastning fra jordbruget 2007-2010. Orientering fra MIljøstyrelsen nr. 1, 2012, Miljøstyrelsen, Miljøministeriet. Avaliable from:
https://www2.mst.dk/udgiv/publikationer/2012/01/978-87-92779-75-5.pdf

Møller, F. & Martinsen, L. 2013: Socio-Economic Evaluation of Selected Biogas Technologies. Scientific Report from DCE – Danish Centre for Environment and Energy No. 62. Aarhus University. Available from:
http://www2.dmu.dk/pub/sr62.pdf

Møller, F. 2009: Velfærd nu eller i fremtiden. Velfærdsøkonomisk og nytteetisk vurdering over tid. Aarhus Unviversitetsforlag.

Møller, H.B. 2016: Personal communication April 2016, Senior researcher Henrik B. Møller, Department of Engineering, Aarhus University.

Nielsen, O.-K., Plejdrup, M.S., Winther, M., Nielsen, M., Gyldenkærne, S., Mikkelsen, M.H., Albrektsen, R., Thomsen, M., Hjelgaard, K., Fauser, P., Bruun, H.G., Johannesen, V.K., Nord-Larsen, T., Vesterdal, L., Callesen, I., Caspersen, O.H., Rasmussen, E., Petersen, S.B., Baunebæk, L. & Hansen, M.G. 2018a: Denmark's National Inventory Report 2018. Emission inventories 1990-2016 – Submitted under the United Nations Convention on Climate Change and the Kyoto Protocol. Scientific Report from DCE – Danish Centre for Environment and Energy No. 272, Aarhus Univeristy. Available from: https://dce2.au.dk/pub/SR272.pdf

Nielsen, O.-K., Plejdrup, M.S., Winther, M., Nielsen, M., Hjelgaard, K., Mikkelsen, M.H., Albrektsen, R. & Thomsen, M. 2018b: Fremskrivning af emissioner. SO_2, NO_X, NMVOC, NH_3, $PM_{2,5}$ og sod. Videnskabelig rapport fra DCE – Nationalt Center for Miljø og Energi, nr. 298, Aarhus Universitet. Available from: http://dce2.au.dk/pub/SR298.pdf

Njakou Djomo, S., Knudsen, M.T., Martinsen, L., Ambye-Jensen, M., Andersen, M.S., Møller, H. & Hermansen, J.E. 2020: Green proteins: An energy-efficient solution for increased self-sufficiency in protein in Europe. Biofuels, Bioproducts and Biorefining 14(3):605-619.

OECD, 2018: Cost-Benefit Analysis and the Environment: Further Developments and Policy Use. OECD Publishing, Paris. Available from: http://dx.doi.org/10.1787/9789264085169-en

Pizzol, M., Smart, J.S. & Thomsen, M. 2014: External costs of cadmium emissions to soil: a drawback of phosphorous fertilizers. Journal of Cleaner Production 84(2014):475-483.

SEGES, 2017: Fodermiddeltabel, revised 14-11-2017. Available from: http://svineproduktion.dk/Viden/Paa-kontoret/Oekonomi_ledelse/Beregningsvaerktoejer/Fodervaerktoejer

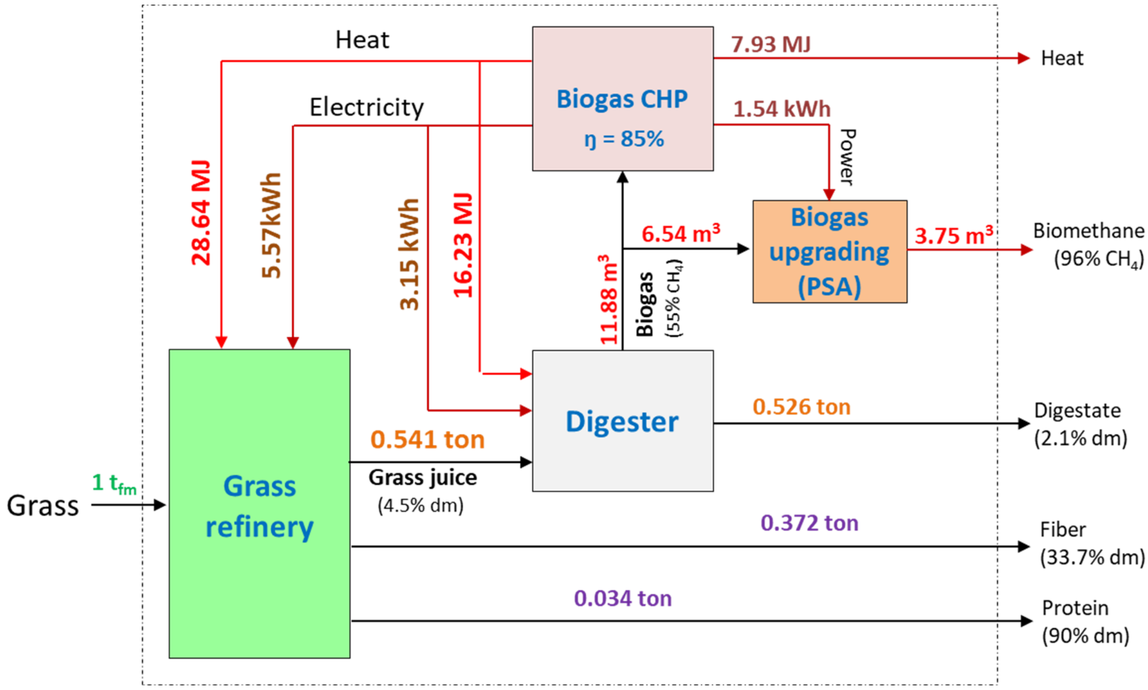
Statistikbanken, 2018. Tabel LPRIS35. Available from: http://www.statistikbanken.dk/statbank5a/default.asp?w=2057

Termansen, M., Gylling, M., Jørgensen, U., Hermansen, J., Hansen, L.B., Knudsen, M.T., Adamsen, A.P.S., Ambye-Jensen, M., Jensen, M.V., Jensen, S.K., Andersen, H.E. & Gyldenkærne, S. 2015: Grøn Biomasse. DCA Rapport Nr. 68, DCA – Nationalt Center for Fødevarer og Jordbrug, Aarhus Universitet. Available from: http://web.agrsci.dk/djfpublikation/djfpdf/DCArapport068.pdf

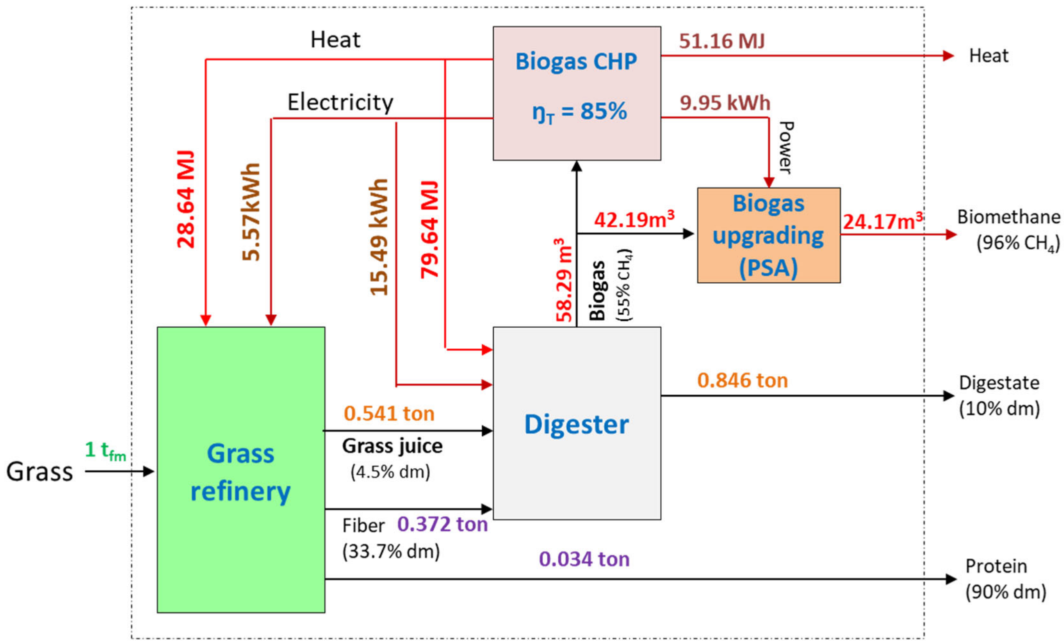
Annex 1 Flow diagrams of biorefinery scenarios

By Sylvestre Njakou Djomo (March 2018).

Small-scale scenario:



Large-scale scenario:



Annex 2 Biogas subsidies

Unit: DDK/GJ															
		Price natural gas		10 DKK/GJ-subsidy		26 DKK/GJ subsidy		79 DKK/GJ subsidy		39 DKK/GJ subsidy		Total subsidy - upgrading		Total subsidy - processing	
	Price index, 2017=1	Fixed prices (2017)	Current prices	Fixed prices (2017)	Current prices	Fixed prices (2017)	Current prices	Fixed prices (2017)	Current prices	Fixed prices (2017)	Current prices	Fixed prices (2017)	Current prices	Fixed prices (2017)	Current prices
2012	0.936							84.4	79.0						
2013	0.952							83.9	79.9						
2014	0.961							83.6	80.3						
2015	0.976							82.7	80.7						
2016	0.982							82.5	81.0						
2017	1	38	38.0	6.0	6.0	41.5	41.5	81.3	81.3	39.0	39.0	128.8	128.8	86.5	86.5
2018	1.02	38	38.8	3.9	4.0	40.4	41.2	80.2	81.8	38.2	39.0	124.5	127.0	82.5	84.2
2019	1.042	37.9	39.5	1.9	2.0	38.8	40.4	80.8	84.2	37.4	39.0	121.6	126.7	78.2	81.4
2020	1.065	37.8	40.3	0	0	37.3	39.7	80.2	85.4	36.6	39.0	117.4	125.1	73.9	78.7
2021	1.087	41.2	44.8	0	0	35.8	38.9	79.5	86.4	35.9	39.0	115.3	125.3	71.7	77.9
2022	1.107	44.4	49.2	0	0	31.1	34.4	79.0	87.4	35.2	39.0	110.0	121.8	66.3	73.4
2023	1.13	47.5	53.7	0	0	26.6	30.0	78.3	88.5	34.5	39.0	104.9	118.5	61.1	69.0
2024	1.153	50.5	58.2	0	0	22.1	25.5	77.7	89.5	33.8	39.0	99.8	115.1	56.0	64.5
2025	1.178	53.2	62.7	0	0	17.8	21.0	77.0	90.7	33.1	39.0	94.8	111.7	50.9	60.0
2026	1.201	56	67.3	0	0	13.8	16.5	76.4	91.8	32.5	39.0	90.2	108.3	46.2	55.5
2027	1.225	58.6	71.8	0	0	9.8	11.9	75.8	92.9	31.8	39.0	85.6	104.8	41.6	50.9
2028	1.25	61.2	76.5	0	0	5.9	7.4	75.2	94.0	31.2	39.0	81.1	101.4	37.1	46.4
2029	1.274	63.7	81.2	0	0	2.1	2.7	74.7	95.1	30.6	39.0	76.8	97.8	32.7	41.7
2030	1.299	66.1	85.9	0	0	0.0	0.0	74.1	96.2	30.0	39.0	74.1	96.2	30.0	39.0
2031	1.325	67.8	89.8	0	0	0.0	0.0	73.5	97.4	29.4	39.0	73.5	97.4	29.4	39.0
2032	1.351	69.5	93.9	0	0	0.0	0.0	72.9	98.5	28.9	39.0	72.9	98.5	28.9	39.0
2033	1.377	71.2	98.0	0	0	0.0	0.0	72.4	99.7	28.3	39.0	72.4	99.7	28.3	39.0
2034	1.404	72.7	102.1	0	0	0.0	0.0	71.8	100.8	27.8	39.0	71.8	100.8	27.8	39.0
2035	1.432	74.3	106.4	0	0	0.0	0.0	71.2	102.0	27.2	39.0	71.2	102.0	27.2	39.0
2036	1.46	75.1	109.6	0	0	0.0	0.0	70.7	103.2	26.7	39.0	70.7	103.2	26.7	39.0
2037	1.488	75.8	112.8	0	0	0.0	0.0	70.2	104.4	26.2	39.0	70.2	104.4	26.2	39.0
2038	1.517	76.5	116.1	0	0	0.0	0.0	69.6	105.6	25.7	39.0	69.6	105.6	25.7	39.0
2039	1.546	77.2	119.4	0	0	0.0	0.0	69.1	106.9	25.2	39.0	69.1	106.9	25.2	39.0
2040	1.576	77.8	122.6	0	0	0.0	0.0	68.6	108.1	24.7	39.0	68.6	108.1	24.7	39.0
Reference:															
Price index, Fixed prices Natural gas: Energistyrelsen (2017): Samfundsøkonomiske beregningsforudsætninger for energipriser og emissioner, maj 2017. Energistyrelsen.															

Annex 3 Heavy metals related to agriculture

In Table A3.1, the input of seven different heavy metals to the fields from deposition and agricultural inputs is assessed for the baseline scenarios with cereal production and the biorefinery scenarios with grass production. The agricultural inputs includes seeds and fertilizer, and it is noted that fertilizer by far is responsible for the greates share of heavy metals originating from agricultural inputs. The calculations are based on Knudsen and Mogensen (Annex 1).

Table A3.1 Heavy metals – changes in input, leaching and emissions to soil induced by shift from baseline scenaios to biorefinery scenarios.

		Input from seed and fertilizer			Changes in leaching			Changes in emissions to soil		
	Deposition	Cereal production	Grass production	Change	Small-scale	Large-scale	Relative change	Small-scale	Large-scale	Relative change
	mg/ha	mg/ha	mg/ha	%	Total (kg)	Total (kg)	%	Total (kg)	Total (kg)	%
Cadmium (Cd)	700	2,899	5,812	100	0.01	0.07	11	4.84	36.34	109
Chromium (Cr)	3,650	40,806	80,814	98	1.66	12.44	4	62.96	472.26	159
Copper (Cu)	2,400	12,259	22,816	86	0.50	3.73	8	- 84.48	- 633.67	- 271
Lead (Pb)	2,400	13,818	31,710	129	0.25	1.85	48	23.03	172.71	92
Mercury (Hg)	50	59	106	81	0.00	0.00	26	- 1.94	- 14.58	- 1,656
Nickel (Ni)	5,475	9,620	18,769	95	-	-	-	- 3.97	- 29.80	- 25
Zinc (Zn)	90,400	87,742	168,335	92	10.50	78.73	32	- 216.77	- 1,625.91	- 3,293

Annex 4 Crop production data

By Marie Trydeman Knudsen and Lisbeth Mogensen, Department of Agroecology, Aarhus University.

Table A4.1 Crop production data for sandy soils.

Sandy soils: JB 1+3										
Crop	**Spring barley**	**Winter wheat**	**Clover grass (not fertilized)**		**Clover grass (fertilized)**		**Grass (medium fertilized)**		**Grass (highly fertilized)**	
Cultivation period	**1 year**	**1 year**	**1-2 years**	**3-5 years**	**1-2 years**	**3-5 years**	**1-2 years**	**3-5 years**	**1-2 years**	**3-5 years**
Input										
N fertilizer, kg N/ha	144	167			240	240	300	300	450	450
N seed, kg N/ha	2	2								
N fixation, kg N/ha	0		225	170	80	50				
N deposition, kg N/ha	14	14	14	14	14	14	14	14	14	14
Total	160	184	239	184	334	304	314	314	464	464
DM content, %	85	85	18	18	18	18	18	18	18	18
CP, %/kg DM	11.2	11.2	19.5	19.2	23.3	24.7	19.0	21.7	23.7	24.9
Output										
N yield main product, kg N/ha	70	80	214	162	292	254	275	257	398	369
N yield by-product, kg N/ha	14	13								
Total	84	93	214	162	292	254	275	257	398	369
N surplus, kg N/ha	76.3	90.7	25	22	42	51	40	57	66	96
Soil N changes, kg N/ha	-10.0	-5.5	8	4	12	10	13	11	19	19
N leaching, kg NO_3-N/ha	**75.3**	**88.2**	**15.9**	**16.4**	**21.6**	**32.0**	**15.2**	**35**	**31.1**	**60.9**
Yield, kg DM/ha	3910	4463	6863	5284	7826	6417	9030	7405	10500	9250
Yield, SFU/ha	4344	5377	5700	4389	6500	5330	7500	6150	8721	7683
Yield, kg/ha	4600	5250	38127	29358	43478	35652	50167	41137	58334	51391

Table A4.2 Crop production data for fine sandy soils.

Fine sandy soils: JB 2+4										
Crop	**Spring barley**	**Winter wheat**	**Clover grass (not fertilized)**		**Clover grass (fertilized)**		**Grass (medium fertilized)**		**Grass (highly fertilized)**	
Cultivation period	**1 year**	**1 year**	**1-2 years**	**3-5 years**	**1-2 years**	**3-5 years**	**1-2 years**	**3-5 years**	**1-2 years**	**3-5 years**
Input										
N fertilizer, kg N/ha	139	173	0	0	240	240	300	300	450	450
N seed, kg N/ha	2	3	0	0	0	0	0	0	0	0
N fixation, kg N/ha	0	0	225	170	80	50	0	0	0	0
N deposition, kg N/ha	14	14	14	14	14	14	14	14	14	14
Total	155	190	239	184	334	304	314	314	464	464
DM content, %	85	85	18	18	18	18	18	18	18	18
CP, %/kg DM	11.2	11.2	18.5	18.2	20.8	21.8	16.7	21.1	23.0	24.9
Output										
N yield main product, kg N/ha	82	101	214	161	290	251	274	263	394	378
N yield by-product, kg N/ha	16	16								
Total	98	117	214	161	290	251	274	263	394	378
N surplus, kg N/ha	58	73	25	23	45	53	40	51	70	86
Soil N changes, kg N/ha	-8	-2	9	6	15	13	18	13	20	20
N leaching, kg NO_3-N/ha	**55**	**66**	**15**	**16**	**20**	**31**	**11**	**27**	**35**	**50**
Yield, kg DM/ha	4548	5610	7220	5540	8700	7200	10250	7800	10700	9500
Yield, SFU/ha	5053	6759	5997	4601	7226	5980	8513	6478	8887	7890
Yield, kg/ha	5351	6600	40113	30776	48334	40000	56943	43331	59444	52775

Table A4.3 Crop production data for irrigated soils.

Irrigated soils: JB 1-4										
Crop	**Spring barley**	**Winter wheat**	**Clover grass (not fertilized)**		**Clover grass (fertilized)**		**Grass (medium fertilized)**		**Grass (highly fertilized)**	
Cultivation period	**1 year**	**1 year**	**1-2 years**	**3-5 years**	**1-2 years**	**3-5 years**	**1-2 years**	**3-5 years**	**1-2 years**	**3-5 years**
Input										
N fertilizer, kg N/ha	162	194	0		240	240	300	300	450	450
N seed, kg N/ha	2	3								
N fixation, kg N/ha			290	250	80	50				
N deposition, kg N/ha	14	14	14	14	14	14	14	14	14	14
Total	178	211	304	264	334	304	314	314	464	464
DM content, %	85	85	18	18	18	18	18	18	18	18
CP, %/kg DM	11.2	11.2	21.7	24.4	18.2	19.3	17.6	18.8	21.0	22.8
Output										
N yield main product, kg N/ha	90	107	276	239	284	247	276	265	396	383
N yield by-product, kg N/ha	18	17								
Total	108	125	276	239	284	247	276	265	396	383
N surplus, kg N/ha	71	86	28	25	50	57	38	49	68	81
Soil N changes, kg N/ha	-7.2	-0.5	12	8	20	17	16	17	24	24
N-leaching, kg NO3-N/ha	**65.5**	**77.4**	**14.7**	**15.9**	**21**	**31.3**	**11**	**21**	**28**	**41**
Yield, kg DM/ha	5015	5993	7946	6119	9752	7997	9801	8800	11800	10500
Yield, SFU/ha	5572	7220	6600	5082	8100	6642	8140	7309	9801	8721
Yield, kg/ha	5900	7051	44147	33993	54180	44428	54448	48889	65558	58334

Table A4.4 Crop production data for loamy soils.

Loamy soils: average for JB 5-6 & JB 7-9										
Crop	**Spring barley**	**Winter wheat**	**Clover grass (not fertilized)**		**Clover grass (fertilized)**		**Grass (medium fertilized)**		**Grass (highly fertilized)**	
Cultivation period	**1 year**	**1 year**	**1-2 years**	**3-5 years**	**1-2 years**	**3-5 years**	**1-2 years**	**3-5 years**	**1-2 years**	**3-5 years**
Input										
N fertilizer, kg N/ha	150	207			240	240	300	300	450	450
N seed, kg N/ha	2	3								
N fixation, kg N/ha			290	250	80	50				
N deposition, kg N/ha	14	14	14	14	14	14	14	14	14	14
Total	166	224	304	264	334	304	314	314	464	464
DM content, %	85	85	18	18	18	18	18	18	18	18
CP, %/kg DM	11.2	11.2	21.7	24.4	18.2	19.3	16.3	18.2	19.35	22
Output										
N yield main product, kg N/ha	104	134	276	239	284	247	274	265	399	391
N yield by-product, kg N/ha	21	22								
Total	125	155	276	239	284	247	274	265	399	391
N surplus, kg N/ha	42	68	28	25	50	57	40	49	65	73
Soil N changes, kg N/ha	-5.2	4.2	12	8	20	17	19	18	28	27
N leaching, kg NO_3-N/ha	**35**	**55**	**15**	**16**	**21**	**31**	**10**	**20**	**21**	**31**
Yield, kg DM/ha	5801	7459	7946	6119	9752	7997	10500	9100	12900	11100
Yield, SFU/ha	6446	8987	6600	5082	8100	6642	8721	7558	10714	9219
Yield, kg/ha	6825	8775	44147	33993	54180	44428	58334	50555	71665	61665

ENVIRONMENTAL AND SOCIO-ECONOMIC ANALYSIS OF INTEGRATED GRASS BIOREFINERY SCENARIOS

This report presents financial and welfare economic analyses of two scenarios for production of green proteins at a biorefinery, integrated with a biogas facility. Residual biomass resources from the protein production provides input to biogas generation, which in turn supplies process energy for the biorefinery, while surplus biogas is upgraded to biomethane. The protein production is based on highly fertilized grasses (450 kg N/ha) that replace conventional crops. The externalities considered in the welfare economic analysis comprise GHG emissions, air pollution, N and P leaching, cadmium as well as road and off-road transport. The analysis shows that protein production in association with biogas generation, based on biomass input of highly fertilized grass, can be commercially attractive, though depending on scale and the specific assumptions made. However, from a public expenditure perspective such production will be burdensome, due to the generous feed-in tariffs awarded to biogas. The negative outcome of the welfare economic analysis indicates that environmental benefits to Denmark do not suffice to justify the level of public support that would be involved. However, the economic value of a potential GHG reduction from less import of soy has not been included, due to its non-domestic features and the uncertainties involved.

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